International Scientific-Technical and Production Journal

The Paton WELDING JOURNAL

September
2004
9

English translation of the monthly «Avtomaticheskaya Svarka» (Automatic Welding) journal published in Russian since 1948

Founders: *E.O. Paton Electric Welding Institute of the NAS of Ukraine*
International Association «Welding»

Publisher: *International Association «Welding»*

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State Registration Certificate
KV 4790 of 09.01.2001

Subscriptions:
$460, 12 issues per year,
postage and packaging included.
Back issues available.

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70 YEARS AT ADVANCED POSITIONS OF TECHNICAL PROGRESS

The Electric Welding Institute was founded by Evgeny O. Paton in 1934 as a constituent part of the All-Ukrainian Academy of Sciences at the facilities of Electric Welding Laboratory at the Chair of Engineering Constructions and Electric Welding Committee. The establishment and all future activity of the Paton Welding Institute are connected with the name of this outstanding engineer and scientist. He defined the main scientific trends of the Institute in the field of technology of welding and welded structures, which are actual at present.

Evgeny O. Paton could foresee the huge prospects in the development of technology of electric welding of metals, the creation N.N. Benardos and N.G. Slavyanov, the talented Russian inventors. The convincing confirmation of this scientific prediction is the indisputable fact that welding today is the leading technological process of a permanent joining of metallic and non-metallic materials under conditions and media, including space and World Ocean. This is a great contribution of the Institute staff for 70 years of its activity.

At the first stage, the Institute specialists proved a feasibility of manufacture of welded structures, being not inferior by their strength and reliability to riveted structures, but even superior to them by some characteristics. This served a basis for mass application of welding in future. At the same years a scientific conception about the arc welding as a metallurgical process was substantiated and the investigations on arc welding automation were conducted under the supervision of E.O. Paton. By 1940 the development was completed and implementation of high-efficient submerged arc welding was started at factories of the country.

The automatic submerged arc welding played an important role during the Great Patriotic War. Directly in the shops of the tank plant in the Urals the Institute associates developed and implemented the technology of automatic welding of armour steel that allowed them to organize the line production of welded bodies of tank T-34 and to mechanize welding of other types of military machinery. Under the shop conditions the Institute staff did not interrupt the research works.

Pre-war and war stages in the Institute activity are the periods of establishment of a scientific school, which authority was confirmed convincingly by giving the name of Paton Evgeny Oskarovich to the Institute in 1945.

In the years of postwar restoration of national economy the efforts of the Institute staff were directed to widening the fields of application of high-efficient automatic and mechanized submerged arc welding instead of manual welding, to the optimization of welded structures and their industrial manufacture. The Institute staff was the first in the world who realized the automatic welding of sheet structures directly in site conditions.

The participation of specialists-welders was widened in the development of weldable structural steels in collaboration with metallurgists for their application in critical welded structures and constructions. The works of this period influenced positively the rates of postwar restoration of industry, the progress in advanced manufacture of building metal structures, manufacture of highly-reliable welded products of heavy, transport, chemical and power industries.

The solution of main problem, such as the increase in productivity and level of mechanization of welding jobs, required the continuous widening of investigations in the Institute to search for new methods and procedures of mechanized welding to increase the rational fields of application of submerged arc welding. The search for feasibility of submerged arc welding of joints, located in different spatial positions, was finalized by the development under the supervision of E.O. Paton of the method of a forced weld formation, which made a good start to the mechanization of arc welding of joints in vertical plane.

On August 12, 1953 the domestic and world science suffered a terrible bereavement: E.O. Paton died at the age of 84. He was the person who added a glorious page to history of the national science and technology. His pupils and successors, all the staff of the Institute continued with dignity the life-work started by his founder. Since 1953 and until now his son, academician Paton Boris Evgenievich, is the director of the Institute.

One of the most remarkable achievements of the Institute of the beginning of the 1950s was the development of the new technology of fusion welding of thick metal, i.e. electroslag welding, which changed radically the manufacture of heavy frameworks, boilers, hydraulic units and other unique welded-rolled, welded-cast structures. Its application allowed producing high-quality welded joints within the wide range of thicknesses.

Later, in collaboration with TsNIITMASh and other organizations, a method of CO_2 welding with thin wire was developed and found the wide spreading in industry and providing the noticeable growth in the level of mechanization of welding jobs. The further development of gas electric welding with consumable electrode was the development of the process and equipment for pulsed-arc welding, welding in mixtures of active and inert gases. In this connection, the importance of works on the creation of semi-automatic machines, which forced out gradually the low-efficient rod electrode welding, where it was possible and rational, should be especially noted.

At the end of the 1950s the investigations in the field of electron beam welding started their rapid development. The efforts of scientists were directed to the study of physical-metallurgical processes in action of powerful (up to 100 kW) sharply-focused beam of electrons on thick-sheet (150--200 mm) structural materials. The especially important problem, solved successfully by the Institute, was the development of technology of closing the circumferential welds which prevented the root defects in the form of cavities, pores and discontinuities.

The further stage in the development of beam technology was its application for the purposes of welding and cutting using laser. Systematic investigations in the field of pulsed and continuous laser welding are carried out at the Institute. Over the recent years the hybrid heat sources such as laser-arc and laser-plasma have been developed by the specialists of the Institute.

At all the stages of the Institute activity a special attention was paid to the study of physical, chemical and metals science peculiarities of welding metals. Laboratories of the Institute were equipped by the research equipment for these purposes.

Investigations in all main trends of pressure welding — flash-butt welding and resistance welding, spot, friction and diffusion welding, were carried out at the Institute.

Physical and technological features of new technological processes of flash-butt welding were studied, systems of automatic control and diagnostics of quality of welded joints were developed. On the basis of the new technologies the manufacture of several generations of specialized and universal machines for flash-butt welding of widely used components, made from low-alloy and high-strength steels and having up to 200,000 mm^2 cross-section area and also from alloys of aluminium, titanium, chromium and copper, have been developed and implemented in industry. Machines for welding rails of different classes in the field and stationary conditions, machines for welding pipes of diameter from 150 up to 1420 mm in construction of main pipelines, installations for welding elements of aerospace engineering structures have found the most wide spreading. Equipment for rail flash-butt welding is exported to many countries of the world.

Using the explosion energy, the new methods of welding, cutting, cladding and treatment of welded joints were created. Explosion welding and cutting can be realized in the field conditions, where the use of cumbersome welding equipment is difficult.

Over many years the Institute carries out investigations in the field of space welding. In 1969 on the board of spaceship «Soyuz-6» V.N. Kubasov, the pilot-cosmonaut, performed for the first time in the world the experiment on electron beam, plasma and consumable electrode welding using unit «Vulkan», designed and manufactured at the Paton Institute. Thus, the start was made for the space technology having a great importance in the program of exploration of space. In 1984 a very important experiment, prepared by the Paton Institute, was performed on the board of orbital station in the open space. Cosmonauts S. Savitskaya and V. Dzhanibekov performed for the first time in open space the processes of welding, brazing, cutting and coating deposition using an electron beam versatile hand tool (VHT). The period from 1985 till 2000 is characterized by the growth in volume of jobs made in space. The works were continued on coating deposition and welding of metals, integrated experiments on deployment of 12 m truss structure, accompanied by welding and brazing of its separate sub-assemblies using VHT, were made, two 15 m truss structures, being the load-carrying base for multiple-use solar batteries of technological module, docked to the orbital station «Mir», were deployed.

In parallel, such complicated problem was also solved at the Institute as mechanization of arc welding under water which became of a great importance in exploration of a near-coast shelf of the World Ocean. Specialists of the Institute have created the equipment for the mechanized arc welding and cutting by a special flux-cored wire at the depths down to 60 m and they are carrying out successfully now the research works on welding application at large depths.

Basic importance was given to the systematic Institute studies in the field of physical-metallurgical peculiarities of welding different metals and alloys by fusion: processes of weld metal crystallization were studied, nature of its structural and chemical inhomogeneity was established, mechanism of pores and cracks formation was studied and measures for their prevention were found. Results of these studies are actually a serious base for the creation and improvement of different types of welding and surfacing consumables.

Intensive progress in modern engineering is accompanied by a constant widening of grades of structural metals and alloys for welded structures. As a result of study of processes proceeding in weld pool, the new welding consumables — electrodes, flux-cored wires, fluxes and gas mixtures, have been developed.

Due to increasing volumes of application of plastics as structural material, the investigations on their welding and, first of all, on welding plastic pipes have been started, including those on adhesion bonding.

Experimental-theoretical studies and scientific developments in the field of strength of welded joints and structures represent traditional trends in subjects of the Institute, which were started by E.O. Paton. Today, these studies have a comprehensive nature and advanced laboratory-test equipment is used for their conductance, the unique full-scale experiments and computer modeling are performed. This allows researchers to develop new effective methods of improving reliability of critical engineering constructions at static and cyclic loads, and also to establish the calculation-design principles of assurance of preset service properties of the welded joints. The problem of creation of reliable welded structures covers also the aspects of selection of materials, rational design solutions, technology of manufacture and erection, reduction in metal content, which are solved successfully by the Institute in collaboration with many branch organizations and enterprises. The intensive works are carried out over the recent years for improving the reliability and life of welded structures, and also for the development of effective methods of their diagnostics.

The works of the Institute are not limited by the investigations in the field of metallic materials. The Institute associates showed also an interest to the problems of welding polymeric materials and products. During recently, one more direction has appeared — electric welding of soft live tissues. Results of these investigations have found their application in practice of surgery operations.

Since the beginning of the 1950s, the search works and experimental developments were started at the Institute by the initiative of Prof. Boris E. Paton for finding the feasibility of use of welding heat sources for producing metals and alloys of super quality and reliability, on the basis of which the main second trend in the Institute activity was formed, namely the special electrometallurgy. Efforts and achievements of the staff in this new field provided a remarkable progress in the development of the national quality metallurgy.

The new electrometallurgical processes include first of all the electroslag remelting of consumable electrode into a water-cooled mould. Fundamental studies of principle of the electroslag process, its physical-chemical, metallurgical and electrotechnical features ensured the advanced positions of the Institute in the development and application of the electroslag technology (cladding, casting, hot-topping, etc.).

Over the recent years a complex of research works has been fulfilled at the Institute, which served a basis for the development of the new generation of electroslag technologies based on producing ingots and billets directly from the molten metal without remelting of consumable electrodes. These technologies are patented in Ukraine and abroad and realized in industry. In particular, a unique complex on production of bimetal rolling rolls of the world level has been created at the Novokramatorsk machine-building plant.

Two more metallurgical technologies have been created at the Institute: plasma-arc and electron beam. Development of technologies and techniques of these remelting processes was carried out in parallel with fundamental studies of physical-metallurgical peculiarities of refining in a controllable atmosphere or vacuum and processes of crystallization of steels, complex-alloyed alloys, non-ferrous and refractory metals.

Plasma-arc remelting has opened wide opportunities for the production of the new class of structural steels — high-nitrogen steels, owing to the comprehensive investigations of gas–metal systems. And the creation of powerful metallurgical plasmatrons allowed the Institute to enter the big metallurgy. New designs of installations of ladle–furnace type of up to 100 t capacity have been developed. The purity of metal, provided in these installations, is not inferior to the electroslag metal by the quality.

Owing to the joint efforts of scientists of the Institute, branch research institutions and manufacturers, the electron beam equipment has been created, and the technology of electron beam melting in vacuum became an indispensable process for producing superquality materials in metallurgy and machine-building. Works in this direction are concentrated now at the Research-Engineering Center «Titan», established at the Paton Institute, which fulfills orders both for enterprises of Ukraine and also for foreign companies.

Investigations of the process of evaporation of metallic and non-metallic materials in vacuum and their subsequent condensation as the basis of a vapour-phase metallurgy gave an opportunity to produce coatings for different materials, including heat-resistant, refractory and composite materials, made it possible to regulate the composition, structure and properties of the deposited layers. Thickness of deposited coatings, depending on purpose of their application, is regulated from tens of micrometers up to several millimeters.

At the beginning of the 1980s a new research trend was formed, namely the integrated investigations for creation of new and improvement of existing technological processes of thermal spraying of protective and wear-resistant coatings. At present, the Institute is developing almost all the advanced processes of deposition of protective and strengthening coatings. Technology and equipment for plasma-arc spraying of wear-resistant coatings, and also equipment for detonation spraying, which can operate using different working gases (acetylene, propane, hydrogen) have been developed.

At all the stages of the Institute activity the development of equipment for mechanization of processes of welding and hardfacing to replace the manual labour of the welder was one of its main tasks. The main principles of design of welding machines, laid by E.O. Paton, are being developed by the staff of Design Office of the Paton Institute taking into account the new tendencies in the progress of welding and metallurgical industries.

A great attention in the Institute is paid to the creation and wide application of automatic monitoring and control of technological processes of welding, special electrometallurgy and spraying using the advanced electronic computational engineering. These developments were based on fundamental studies of definite technological processes as objects of control. The first investigations in this field were started by Prof. Boris E. Paton as far back as during the Great Patriotic War and are being developed successfully now by his direct supervision.

A great contribution to the creative achievements of the Institute staff was made by those divisions and scientists dealing with mathematical investigations, developing new methods of modern physical and chemical investigations, creating information systems, databases and expert systems, dealing with prediction and systematic analysis of economical aspects in the progress of welding science and technology.

Owing to the combination of purposeful fundamental theoretical studies with engineering-applied developments, close creative collaboration with industrial enterprises in realization of technological innovations, the Institute for the 70 passed years of its activity was transformed into the largest research center in the field of welding and allied technologies in the country and in the world.

Today, the Institute is the scientific-technical complex, which incorporates the experimental design-technological bureau, three pilot plants, a number of engineering centers. All its subdivisions have in total a staff of about 3500 persons, 1700 among them are working at the Institute proper. The scientific potential of the Institute amounts 300 scientists, among them 8 academicians and 6 correspondent-members, 72 Dr. of Techn. Sci. and more than 200 Cand. of Techn. Sci.

The activity of the Institute and self-financing subdivisions is strictly coordinated and oriented completely for the joint solution of problems in main scientific directions.

Active and direct participation of the Institute scientists in a practical realization of their developments increases their importance as workers of the academic science in the conductance of fundamental studies and search developments in the field of welding and allied processes, and also special electrometallurgy, having an interindustry importance. During 70 passed years the Institute has proved the vitality of orientation to the purposeful fundamental investigations. On the credit side of the Institute scientists there are unique results in knowledge of physics of arc discharge and low-temperature plasma, properties of powerful sharply-focused electron beams, nature of melting, evaporation, crystallization and condensation of metals, physical-chemical and thermophysical processes of welding and refining remelting, strength and reliability of welded joints and structures.

Results of these works were confirmed by licenses and patents. Institute sold more than 150 licenses to the USA, Germany, Japan, Russia, Sweden, France, China and others. About 2600 patents of Ukraine, Russia and foreign countries and also by more than 6500 author's certificates were obtained.

Over the years of the Institute activity more than 60 outstanding developments, made and implemented in the national economy by the Institute specialists in collaboration with industrial workers, were awarded by Lenin, State prizes and also the prizes of names of the famous scientists of Ukraine.

Realization of challenging scientific developments and innovation projects of the Institute is also realized by Technological Park, organized at the Paton Institute, including above 30 research institutions, enterprises, engineering centers and pilot plants, specialized in the field of welding and allied technologies. Among them, such well-known manufacturers of welding equipment as KZESO and SELMA.

One of main trends in the Institute activity is the education and training of scientific and engineering staff. There are post-graduate coarses and the specialized council on approval of theses for defence in the field of welding, special electrometallurgy and automatic control of technological processes.

Education of engineering staff is carried out together with National Technical University of Ukraine «Kiev Polytechnic Institute». Scientists of the Institute deliver review courses to the students and supervise the purposeful preparation of masters. Scientific-industrial and diploma practical works are made in research departments and laboratories of the Institute.

Education of engineers-physicists and mathematicians for their work in the field of welding and special metallurgy is realized at the Chair of Physical Metallurgy and Materials Science of Kiev Division of Moscow Physical-Technical University organized on the base of the Paton Institute.

Professional-technical training and retraining of specialists of welding industry is performed at the Educational Center of the Institute. System of education in the center is very flexible. Structure of educational programs envisages both grouped and also individual education and training of audience of courses. Training is realized in accordance with National and European standards with issue of appropriate certificates.

Center of certification of products of welding industry, which was accredited as a body of certification, named SEPROZ, has been created on the base of the Institute, having a unique scientific and staff potential, well-equipped test laboratories. At present the Center carries out work on improvement of certification system in accordance with International rates and rules.

Institute has wide international relations with leading centers of welding in Europe, the USA, Asia. It is the member of International Institute of Welding and European Welding Federation. Interstate Scientific Council on Welding and Related Technologies of CIS countries, International Association WELDING and International Assosiation INTERM are functioning at the Institute facility.

Results of investigations of the Institute scientists are continuously published in journals «Avtomaticheskaya Svarka», «Sovremennaya Metallurgiya», «Tekhnicheskaya Diagnostika i Nerazrushayushchy Kontrol», «Svarshchik», manuscripts, handbooks and other books are issued. In addition, the Institute publishes «The Paton Welding Journal» and «Advances in Electrometallurgy» in English.

Institute organizes different conferences and seminars, national and international exhibitions.

A glorious way was passed by the Institute during 70 years. Today, the Institute is the union of like-minded persons, multiplying the success of Paton scientific school having a world recognition. The Institute is growing and progressing, its structure and management system are updated and all this is directed to the further development of welding and allied processes, and also to the solution of basic problems of economy of the industrial production.

ELECTRIC WELDING OF SOFT TISSUES IN SURGERY

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Main drawbacks of the available methods for joining soft tissues in surgical operations are noted. It has been established that under certain conditions it is possible to join incisions in different organs and soft tissues by the method based on heating the joint zone by high-frequency current. This method has much in common with the resistance welding method, that is why it is called welding. Multiple experiments made on animals, and later in clinics, confirmed that the application of welding in surgery is feasible and highly promising. More than 2,000 patients were operated in the clinics of Kiev. Surgical operations are mentioned, which are characterized by the efficient application of welding, and which were verified and mastered by the Kiev clinics.

Keywords: *electric welding, soft tissues, joint, surgery, equipment and tools, advantages*

The most important tasks of modern surgery are development and introduction into clinical practice of new methods of joining the organs and tissues, simple to perform for the surgeon and favourable for the patient. Existing traditional methods of restoring the continuity of tissue using suture materials, stitching devices, adhesive compositions and other means are imperfect.

When suture materials are used, there is risk of circulation disorder developing in the zone of applying the sutures, migration of microorganisms along the suture threads, which may lead to development of purulent complications, peritonitis, granulomas, anastomositis and perianastomositis. There is also a real risk of development of allergic reactions of the body to the extraneous object. This is exactly why an ever growing number of surgical research is devoted to searching for new methods of tissue joining.

A widely used method of joining the tissues using staplers envisages the application of suture analogs, namely metal staples, remaining in the tissues and having the same drawback as the sutures. In addition, a pronounced ischemia of the tissues being joined is observed in the compression zone, which makes the anagenesis more complicated.

Adhesion bonding of tissues through a number of reasons known to medical specialists did not become widely used, either.

Laser welding does not provide the required strength of the joints. Laser heating with a protein-based «solder» has a certain potential for application in surgical practice, however, a too complicated technology can impede its wide application.

Electric welding to join incisions of live tissues and organs during surgery was applied for the first time by the team of researchers of the E.O. Paton Electric Welding Institute of NASU in cooperation with the scientists and specialists of the experimental department of the Institute of Surgery and Transplantology (IS&T) of AMSU with participation of International Association «Welding» and active financial support of CSMG Company, USA. First a series of experiments were performed on animals with participation of microsurgeons of «Okhmatdet» Association. This effort was supported by US surgeons led by a well-known American Prof. J. Kuts from Louisville. Results of initial experiments of the Ukrainian team were demonstrated to American specialists in the USA two times. As in the next stage attention was focused on general surgery and engineering problems, the team was joined by staff members of the Central Clinical Hospital of the Military-Medical Administration of SSU (clinical base of the National Medical University). Microsurgery research was postponed until perfect equipment has been developed, and positive results in general surgery have been obtained using this equipment.

Experience of application of electric surgery for cutting tissues and hemostasis is about one hundred years long. Research team became interested in one of electric surgery techniques, so-called bipolar coagulation. During its performance, a high-frequency electric current passes through the walls of a «compressed» vessel or fine vessels, causing their heating. At temperature above 50--55 °C the proteins contained in the tissue –– globulins start «unwinding» and intertwining, which results in joining of the compressed vessel walls, thus preventing the hemorrhage. Coagulation rate essentially depends on temperature: the higher the temperature, the faster do the proteins coagulate.

Bipolar coagulation is often used for sealing vessels of up to 1.5 mm diameter. A vessel sealed by bipolar coagulation can stand a pressure much higher than arterial pressure without loss of tightness.

Our first research showed that under certain conditions bipolar coagulation allows joining not only the walls of a thin vessel, but also a large number of other layers of different organs and tissues. However, it was still necessary to clarify what is required to be able to use bipolar coagulation to join tissues in the place of incisions, instead of the traditional suturing using sutures or metal staples. It was also necessary to ensure a reliable joining of the organs or tissues, guaranteeing their functioning in the early post-op-

Figure 1. Power source with built-in controls

erational period and the fastest possible recovery of the operated organ.

Numerous experimental studies showed that the reliability of joining the organs and tissues depends on many factors, in particular, shape of the high-frequency current curve, shape of the thermal cycle curve, absolute values of frequency, temperature of heating the tissue sections being welded and electrodes compressing these sections, specific pressure of the electrodes, duration of tissue heating, its physical properties, etc. A reliable joining of the tissues is only possible at a favourable combination of the above factors.

The process of joining the organs and tissues is similar to resistance welding and has a lot of common features with it. Therefore, further on we will call this process welding.

In order for the restoration of the physiological functions of the operated organ or tissue to proceed quickly enough and without complications, the thermal impact, on the one hand, should be minimum, and, on the other, it should be sufficient for producing a reliable joint. This, alongside all the other features, is exactly what makes the welding process different from the traditional process of bipolar coagulation, at which tissue overheating in the point of electrode location or incorrect application of the process may lead to the tissue loosing its viability. It is also important that the welding equipment and welding tools are simple and convenient for the surgeon, do not distract his attention and do not lead to any waste of time. Therefore, special attention should be given to development of the system of automatic control of the welding unit.

Our team managed to largely solve the problems, related to welding the soft tissues, and develop laboratory equipment with an automatic system for welding process control required for checking the engineering solutions, and take it to the stage of application in general surgery and gynecology.

Equipment and surgical tools. It is found that the widely used coagulation equipment is not suitable for welding. Scientists and specialists of the E.O. Paton Electric Welding Institute of NASU in co-operation with doctors managed to determine the specific requirements made of the welding equipment. These include, in particular, the above-mentioned requirements. In addition, it was necessary to find the methods of self-adjustment of the system of high-frequency power supply, providing formation of welded joints with the least thermal impact on the tissue under the conditions of possible variation of the thickness of the layers being welded and their physical properties. Adjustment of the control system should be performed automatically, without distracting the surgeon from performance of his main functions. Performance of complex investigations resulted in development of a method to join soft tissues, of a device and tools for its embodiment. Ideas incorporated into the development were recognized to be novel and patents were granted for them [1–7]. Versatility of the equipment should be regarded as its definite advantage. The equipment can be advantageously used as a coagulator for cutting, as well as to produce circumferential and linear welds in one cycle. One of the models of the power source with the built-in control equipment is shown in Figure 1.

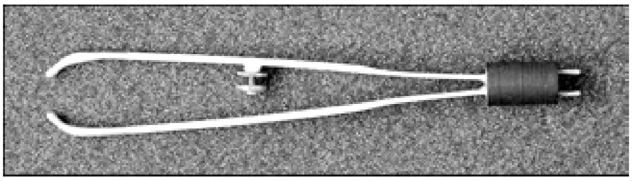

Figure 2. Bipolar forcepts for welding

The tools are made as bipolar tools (Figures 2–5). Forcepts and clamps are used most often. In those cases when it is difficult for the surgeon to control the pressure, judging only by the force of the fingers holding the tool, the forcepts are fitted with special devices. It should be noted that pressure stabilization plays a significant role. As the tissue has low elasticity, the greater the force of the electrodes clamping the tissue, the smaller the volume being heated, which invariably affects the final results in a certain way. At excess pressure electric breakdown of the layers being welded is inevitable, and, contrarily, at insufficient compression the heated volume is too large.

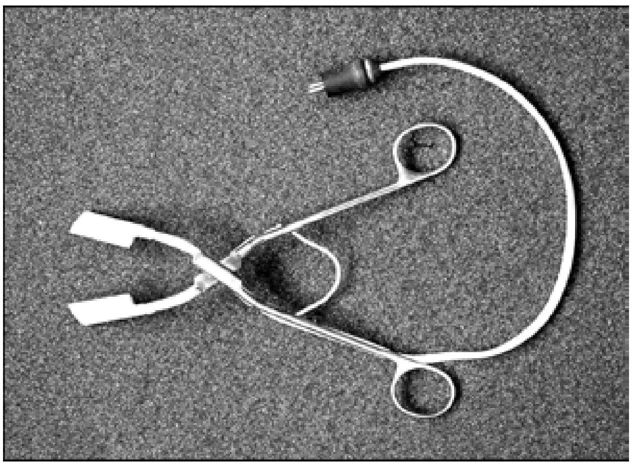

Figure 3. Clamp for welding

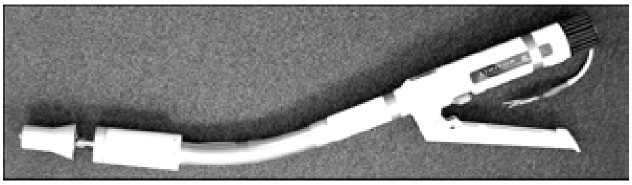

Figure 4. Tool for butt welding (end-to-end) of the intestina

A lot of attention was given to the shape of the working surface of the electrodes, and material for their manufacture. The latter should meet the conditions of a long-term use (with short intervals) without overheating. One of the important indices of surgery is the speed of its performance which determines the time of a patient being under anaesthetic. Electric welding is promising in this respect also, as the developed specialized tool minimizes the time for making the joint. In particular, such a tool (Figure 4) enables welding to be performed as one cycle for 2–3 s. Application of welding is also effective in laparoscopic operations, using specialized tools (Figure 5).

Experiment on animals. Development of tools, power source, control system and software was performed in close co-operation by engineers and doctors-experimentalists. Each technical solution was verified on animals, precised many times and again verified. Medical studies were performed simultaneously.

Operations were initially performed on white rats. After the fundamental possibility of welding the live tissues was proved, a large test series was run on rabbits. The following surgery was performed: closing the cholecystomic wound, appendectomy, closing the gastrotomic wound, forming end-to-end and side-to-side anastomosis of the large intestina, electroresection of the liver and welding up a wound in the urinary bladder. After applying a death lethal injection to animals at the age of 4 years the comparative evaluation of the formed joints was performed, in terms of the degree of necrobiotic changes in the joint zone, extent of necrotic changes in the joint zone, condition of mucous epithalisation, presence of cicatricial stenosis and other adhesions. Particular attention was given to studying the condition of interintestina anastomoses, made with application of the welding technology, and their comparison with the suture anastomosis in the traditional procedure.

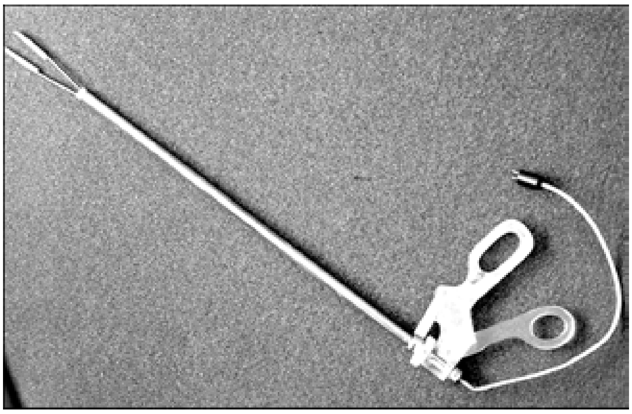

Figure 5. Tool for laparoscopic operations

The final stage of experimental studies were operations using the welding technology on a control group of pigs of 20 to 25 kg weight (45 animals). Selection of the animal species was due to the fact that the structure of biological tissues of the pig and man is greatly similar. One of the main purposes at this stage is statistical evaluation of electric welding as an element of the surgical technology. One of the first operations on pigs was welding the wall of gall bladder. Compared to cholecystotomy with a staple weld applied with «Autosuture» stapler, the results of welding in terms of epithelization, intensity of postoperational adhesions and scar thickness were preferable. This was followed by operations on forming the Braunian anastomosis at application of cholecystoentheroanastomoses. Good results allowed going over to operations with formation of large-small intestina anastomoses with welding forcepts, and then applying end-to-end anastomoses of the large intestina using special devices, providing joining of the intestina in one cycle. Operations on the large intestina yielded quite encouraging results. Six months after surgery the weld line could only be identified morphologically. All the anastomoses were viable, passable, and functioned well.

Experiments on coagulation of liver tissue in the zone of electrode action in the appropriate welding modes were conducted at the same time. A coagulation fissure of up to 60 mm was formed, this allowing bloodless resection of the liver.

Animals from the control batch were taken out of the experiment after 14, 30, 60, 90 and 180 days. All the postoperational animals survived. No complications related to surgery were observed. Conducted studies established a reliable ground for a wide introduction of electric welding process as the main and auxiliary method to bond biological tissues in operations in clinical practice.

Experience of welding application in clinics. Conducted at IS&T experimental studies of welding live tissues of animals allowed going over to stage-by-stage clinical application of the developed process on man in the Central Clinical Hospital of SSU MMA and at IS&T. At the start welding was applied at a distance from the organs and on human tissues, procedure of making the joint and its modes were optimized. Then the welding technology was used to perform open surgery on the organs or that part of them (stomach, intestina), which was to be removed.

Operation with application of electric welding tools on man (joining a stomach wound after gastrotomy) for the first time in the clinical practice was made in the Central Clinical Hospital of SSU MMA in June, 2000. Later on operations on the gall bladder (Figure 6), cystic duct, fallopian tubes and other organs were performed in the same hospital. Tools were developed for welding the gall bladder, gall-ducts, large and small intestina, fallopian tubes, uterus, peritoneum, skin aponeurosis, subcutaneous fat. Successful performance of 44 operations enabled the Ministry of Health of Ukraine issuing a certificate of registration of the equipment for welding organs and tissues and allowing its clinical application.

This equipment is currently applied in several clinics of the city of Kiev (City Hospital No.1, Chair of Thoracic Surgery and Pulmonology of the Academy of Post-Diploma Education with «Polytrauma» Ward of Hospital No.17), as well as in the Donetsk Oncology Center. Electric welding is currently used to perform operations in many fields of surgery. More than 2,000 patients have been operated on without a lethal outcome or serious complications. Nonetheless, a lot is still to be done to widen the areas of application of electric welding, and improvement of surgical techniques. This will require, first of all, widening our knowledge of the tissues as a specific electrically conducting medium and the phenomena proceeding in it at heating, improvement of the equipment and development of specialized tools for a fast performance of the joints. All this is to be implemented in the future, and now it is necessary to wider apply the developed equipment, which, as shown by the experience of application in the clinics, yields good results.

In May of this year a delegation of Ukrainian scientists and specialists demonstrated in the USA to US surgeons and representatives of the medical industry the capabilities of the welding process in surgery. All those present positively evaluated the work done by Ukrainian scientists. In particular, Prof. J. Kuts, present at demonstration operations, noted that performance of such operations (on the intestina, liver and other organs) can lead to a revolution in surgery in the next few (2–5) years.

Advantages of welding compared to the traditional methods of joining the tissues. Experience of welding application under the clinical conditions confirmed its effectiveness. An important result is prevention of development of such serious consequences of application of sutures, staples or adhesive, as:

• inevitable development of inflammation reaction to their presence in the wound;

• risk of infection propagation from the hollow organs (intestina, stomach) along the suture material with subsequent development of grave postoperational complications;

• risk of stenosis of the anastomoses as a result of development of rough scar tissues in the remote postoperational period, etc. During performance of operations on the gall-bladder and urinary bladder the «foreign bodies» may lead to concretion formation.

Electric welding is promising for formation of anastomoses between the tubular and hollow organs due to a lower risk of development of anastomosites, stenoses, infection in postoperational wounds, formation of granulomas, seromas, ligation fistula often requiring rather prolonged treatment.

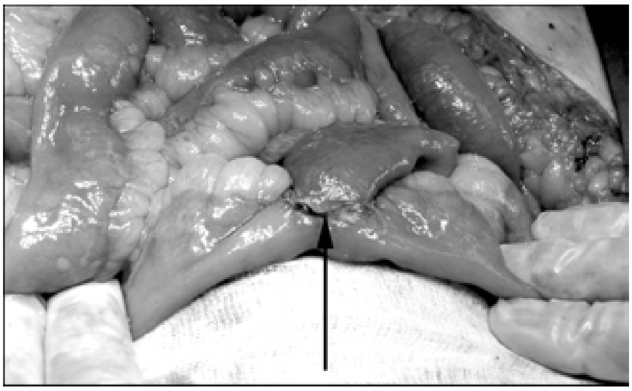

Figure 6. Weld (*shown by an arrow*) in the section of gall bladder right after welding

Application of electric welding in operations on the liver and spleen allows reaching the maximum hemo- and cholestatic effect, and energy concentration in strictly localized regions allows avoiding damage of the main tubular structures (arterial and veinous vessels, gall-ducts).

Use of welding technologies allows fastening surgery performance by 20 to 40 min on average, and reducing blood loss by approximately 200–250 ml, and sometimes even several times more, achieving the cost effectiveness due to reducing the cases of application of expensive equipment and staplers, saving the sutures, staples, etc.

Advantages of electric welding are particularly significant when combined with the endoscopic and laparoscopic methods of surgery, which mutually enhances the advantages of each of the above methods separately (reliability, low traumatism, mini-invasiveness).

Electric welding should be highly promising during performance of restoration operations on the organs of the gastrointestinal tract first of all of the entire intestina, stomach, with formation of anastomoses, in particular, end-to-end, side-to-side for a temporary or final sealing of the sections of the above organs after removal of the pathology focus.

In clinical practice the welding technologies may also be widely used in time-urgent surgery in case of acute appendicitis, traumas of parenchymatous organs (hemostasis, resection of the smashed part of the organ), perforating peptic ulcers, traumatic damage of the lungs, etc. Welding of the damaged walls of gall-bladder, distal part of the common gall-duct, performance of bilio- and pancreatodigestive anastomoses, technically difficult to perform by other methods, extraction of cysts and liver hemangiomas — this is a by far not complete list of indications for application of electric welding of organs and tissues in surgery of the hepatobilioary system.

A fine scar in the zone of anatomized organs increases the prospects for application of the above method in those areas of surgery, where the suture or instrumental weld is difficult to perform. This is application of bilio- or pancreatodigestive anastomoses, operations on restoration of the permeability of fallopian tubes. Stenoses of anastomoses are particularly complicated, as they change the anatomy and functions of the anastomized organs. This problem should be also addressed using electric welding.

Welding technologies should find wide application in gynecological practice, first of all in restoration of the permeability of fallopian tubes in case of infertility of different aetiology, abdominal pregnancy (fine scar, less risk of its stenosis due to scarring), as well as in performance of such traumatic and risky operations because of complications as extirpation and supravaginal amputation of the uterus, which are done practically without any blood loss.

A significant effect, as shown by the first results, can be obtained in proctology.

Obtained experimental results suggest a quite real application of electric welding in vascular surgery, neurosurgery, where formation of a fine scar in the operation zone is important, in prevention of vessel stenosis, etc. We believe that in the near future the welding technologies will be used with success in transplantology in formation of vascular anastomosis and in lung surgery.

In urological practice tissue welding can be applied for closing the wounds of the urinary bladder, urethra, end-to-end joining of damaged ureters.

Application of welding technologies is also promising in laryngology. The first samples of welding tools were currently developed for these purpose, which were transferred to the Central Clinical Hospital of MMA of SSU and have found clinical application there.

There is no doubt that the fields of rational application of welding will expand in the future. This is very evident from the results of its use in the clinics. The current subject of discussion is the urgency of solving the problem of providing the capability of doing surgery in remote regions, where medical assistance is absent, for instance, in space or in the pilot stations. Further on use of robots can be anticipated, which will be remotely controlled from a long distance by a qualified surgeon through TV systems. Under the above conditions welding will simplify the operation and will allow it to be performed with better results and less blood loss.

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THEORY AND PRACTICE OF TIG-F (A-TIG) WELDING (REVIEW)

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Results of investigation of the effect of fluxes on the process of argon-arc tungsten-electrode welding are considered. Special attention is given to analysis of factors that cause increase in operational characteristics of the arc and, in particular, increase in the penetration depth. It is assumed that increase in the penetration depth is caused by growth of the Lorentz force due to contraction of the arc by flux and increase in current density in the anode region. The effect exerted by changes in the gradient of surface tension of molten metal in the weld pool on penetration is of a secondary importance.

Keywords: *arc welding, tungsten electrode, argon, arc plasma, current density, penetration depth, flux, dissociation*

Argon-arc tungsten-electrode welding over the flux layer, i.e. A-TIG welding, has attracted a considerable scientific and industrial interest in recent years. Deep penetration of metal, narrow welds, small size of the heat-affected zone, relatively low heat input and, as a consequence, decreased residual welding strains — this is just an incomplete list of advantages of A-TIG welding.

At the same time, researchers have diametrically opposite opinions as to the main factor responsible for these advantages and deep penetration in particular. Some authors are of the opinion that flux decreases surface tension of liquid metal and radically changes direction of the convective flows and heat transfer in the weld pool, thus leading to increase in the penetration depth. Other authors see the cause of this phenomenon in contraction of the arc and increase in the pressure it exerts on the molten metal.

The purpose of this article consists in an attempt to provide the most reliable interpretation of those processes and phenomena that cause increase in the penetration depth in A-TIG welding on the basis of analysis of publications and long-time research conducted by the authors.

The process of argon-arc tungsten-electrode welding over the flux layer was developed by the E.O. Paton Electric Welding Institute in the middle of the 1960s. It was initially intended for titanium and then for steels and copper-base alloys [1–5], thus receiving a wide commercial application. Presentation of this process at TWI (1993) attracted interest of specialists from a number of countries and gave impetus to its further comprehensive study. The point is that the use of fluxes in tungsten-electrode inert-gas welding exerts a strong effect on the welding process, and first of all on the weld formation. The presence of a flux layer on the weld edges leads to a substantial expansion of technological capabilities and raises efficiency of the TIG welding process [6–8].

This effect of fluxes was fixed in TIG welding of alloys with different thermal-physical and physical-chemical properties, such as different grades of steels [7–9], alloys of titanium [10], copper [11], nickel [12], magnesium [13], etc. Therefore, it is of a universal character. That is why, welding over the flux layer can be regarded as an independent process or, at least, as a modification of tungsten-electrode inert-gas arc welding, like plasma-arc welding. Here we have to note certain incorrectness, in our opinion, of the term «A-TIG» for this welding method, as fluxes used for TIG welding do not affect the energy of activation of any process, activate no processes and, therefore, are not «activators» of anything. We believe that abbreviation TIG-F is a more appropriate term for this welding method.

The very first publications dedicated to studies of the effect of fluxes on the argon-arc tungsten-electrode welding process noted a number of specific phenomena occurring in the arc, which were then confirmed by further investigations. It was established that independently of properties of base metal, the presence of flux in the welding zone leads to contraction of the arc column and increase in the arc voltage [2, 13–16]. Flux increases the current density at the anode [8, 17, 18], as well as the absolute value and gradient of temperature in the arc plasma [13, 19, 20]. It should be noted that the depth of penetration and extent of the above changes in the welding arc are interrelated and depend, other conditions being equal, upon the chemical composition of flux and its quantity on the weld edges [8, 9, 13, 14, 21, 22].

The main causes of contraction of the arc are also known. First of all, this is a reduction in size of the region where the anode spot can exist. The molten flux is forced out to periphery of the weld pool and the adjoining region of base metal under the effect of the arc pressure and shielding gas flow. As a result, an insulating layer is formed around the weld pool because of a dramatic difference in electrical conductivity between the liquid metal and molten flux [14, 20], thus making the welding current flow only through the central part of the weld pool bounded by this layer. Size of this part of the pool is determined by the adhesion of flux to metal welded, i.e. the Gibbs energy of reactions of interaction between them [2, 23].

Vapours of flux and products of its interaction with metal welded play no less important role in contraction of the welding arc [2, 6, 8, 10, 13–15, 23–26]. However, there is no agreement among researchers regarding the contraction mechanism. This is explained primarily by different views as to the presence and character of distribution of vapours in the arc gap. Thus, the authors of studies [13, 15, 24] suggested the presence of the vapours of flux, base metal and even tungsten electrode [13] in the arc column, as well as the cathode and anode regions. On this basis, they could not explain [24] constancy of the effective ionisation potential and temperature increase in the arc column in the case of adding fluxes containing low-ionisation potential elements to the arc zone. Moreover, the model they offered to describe contraction of the arc by negative ions of halides [24] has never been confirmed experimentally, as it suggests that the chloride flux, for example, is universal for welding metals with different physical-chemical and thermal-physical properties.

In study [15], contraction of the arc by flux in welding steels is considered exclusively from the standpoints of its content of electronegative elements, such as oxygen. The focus in this study is on chemical reactions occurring on the surface of the weld pool and interaction of plasma flows in the arc. It should be noted, however, that the purely fluoride flux [27], which prevents the probability of occurrence of such chemical reactions, provides in welding of steels no less substantial arc contraction and penetration depth than fluxes containing oxides.

Reference [13] is the only study which suggested that the flux vapours in welding are most probably located in the peripheral region of the arc.

It was experimentally found [28–30] that plasma of the argon arc in TIG and TIG-F welding contains no impurities. The vapours of flux and consumable anode do not penetrate to the arc column, and their glow looks like a hollow cone on the periphery of the argon plasma.

Based on generalisation of the results of theoretical and experimental investigations [2, 8, 14–19, 24–31], study [23] suggested a theoretical model of contraction of the arc under the effect of flux in TIG-F welding. The model describes contraction of the positive column of the arc and its anode spot as a result of interaction of a combination of factors. They include screening of metal about the weld pool by liquid flux, stabilisation of the pool within the anode spot zone, increase in thermal conductivity of the arc gas caused by the processes of dissociation and molisation of the molecular flux vapours, as well as de-ionisation of peripheral regions of the arc as a result of capture of the conduction electrons by the electronegative particles of the vapours of flux and products of its interaction with metal welded. The model allows analytical evaluation of the size of the electrically conducting region of the arc column. Naturally, the degree of the effect exerted by each of the above factors on the arc contraction may differ depending upon the type of metal welded and the composition of flux.

Causes of variations in the penetration shape in the case of using fluxes are less studied [8, 32]. There is no agreement as to the mechanism of the effect of flux on the penetration depth. Some researchers are of the opinion that arc contraction and increase in energy density in the anode spot lead to increase in the penetration depth, although they give no data to explain the mechanism of this increase. Other researchers think that the main cause of deep penetration lies in change of the gradient of surface tension of liquid metal in the weld pool and, as a consequence, in change of the Marangoni flow direction. However, the effect of the flow of liquid metal in the weld pool caused by the surface tension gradient on the penetration depth was studied experimentally only for the case of surface-active elements contained in base metal. Therefore, the results obtained do not apply to fluxes for TIG-F welding [8].

In study [20] the penetration depth in TIG-F welding was predicted by the calculation method, allowing for possible causes of the effect of flux on the penetration shape [6, 15, 33, 34]. Referring to studies [15, 34], the authors suggested that decrease in surface tension of molten metal by flux may lead (under the effect of the arc pressure) to formation of a deeper crater on the surface of the weld pool and, accordingly, to increase in the weld depth.

However, as shown by the calculations, the penetration depth that can be provided due to a lower surface tension of liquid metal (other conditions being equal) is much smaller than that in the real welds made with the assistance of flux.

It was concluded, therefore, that the change of the penetration shape in TIG-F welding is not related to the possible effect of flux on the level of surface tension of molten metal in the weld pool. At the same time, the penetration depth considerably increased if a flux was assumed to change the temperature dependence of surface tension of liquid metal from drooping to rising.

As follows from study [33], the temperature gradient and, hence, the surface tension gradient causing the convective Marangoni flow are formed on the surface of the weld pool during the welding process. Liquid metal flows over the weld pool surface from the region with a lower surface tension to that with a higher surface tension. If surface tension decreases with increase in temperature, which is typical of pure metals, the flow is directed from the centre of the weld pool to its periphery.

Heat transfer has the same direction, thus leading to widening of the weld and decrease in its depth. In the case where surface tension increases with increase in temperature (in the presence of surface-active elements), the flow of metal is directed from the periphery of the weld pool to its centre. The effective heat transfer occurs in the same direction, and the welds become deeper and narrower.

The gradient of surface tension is formed also as a result of segregation of impurities on the weld pool surface. For example, surface tension in the hottest central part of the weld pool will grow because of a more intensive evaporation of surface-active elements taking place here, thus leading to formation of the centripetal Marangoni flow. This is another proof of the fact that the increased penetration in flux-assisted welding is not related to growth of surface tension of molten metal in the weld pool and formation of a deeper crater in it [15, 34].

Having comprehensively studied the effect of surface-active elements on the weld shape, the authors of study [35] established that selenium, for example, is favourable for formation of narrow and deep welds on stainless steel in TIG and laser welding, and proved validity of the model of penetration provided by metal flows in the weld pool caused by the surface tension gradients. However, under certain welding conditions, such as high values of the welding current, other factors, and the Lorentz force in particular, dominate in the penetration mechanism. Study [35] notes also the absence of any data on the effect of the flows of liquid metal in TIG welding of non-ferrous metals.

Assuming that the weld shape in TIG welding is determined primarily by convective flows in the weld pool, the authors of studies [36, 37] considered possible driving forces for these flows. They include aerodynamic drag driven by the cathode flows in the arc (friction force), buoyancy force generated because of a different density of metal in the pool (buoyancy), electromagnetic Lorentz force and gradient of surface tension of liquid metal. The friction and buoyancy forces in all the cases are directed outward from the pool centre, and the Lorentz force is directed from periphery of the weld pool to its centre.

Direction of the action of forces driven by the surface tension gradient depends upon the presence and concentration of surface-active impurities in metal and upon the distribution of temperature in the weld pool. As a rule, the buoyancy force is insignificant. So, it is usually ignored and consideration is given to the balance of three forces.

In conventional TIG welding, convection in the weld pool influenced by the cathode flow and Marangoni effect has a centrifugal direction, and heat coming from the arc is transferred to the periphery of the weld pool. This results in wide and shallow welds. Meanwhile, surface-active elements, and oxygen in particular, which is contained in fluxes for welding of steels, cause change in the surface tension gradient and, as a consequence, the Marangoni flow direction. It suppresses the centrifugal convection from the cathode flow. The arc heat is transferred inward to the weld pool centre. The penetration increases, and the weld width decreases. In the case of flux-assisted welding, consideration should also be given to increase in the Lorentz force [38] resulting from growth of the current density at the anode, which is another factor promoting deepening of the penetration and decreasing the weld width.

The most comprehensive consideration of the effect of the arc pressure in TIG welding on the weld shape is given in study [38]. All the investigations dedicated to this issue deal with the force effect of the arc on the anode (metal welded), rather than with the pressure proper. The former is composed of the gas flow dynamic head (gas-kinetic forces) and volume electromagnetic forces generated in a conductor by interaction between the current and self-magnetic field.

Longitudinal component of the electromagnetic field directed towards the weld pool is formed in the conical welding arc. The same force was formed in the pool proper, causing the centripetal motion of liquid metal in it. This force (Lorentz force) grows with increase in the welding current and its density [39–41].

On this basis, the authors of study [17] suggested that fluxes provide a dramatic increase of the Lorentz force, cause formation of the flow of liquid metal directed inward to the weld pool and, hence, the heat, thus leading to increase in the penetration and decrease in the weld width.

If a flux contains sufficient amount of surface-active elements (for metal welded), and if the temperature dependence of surface tension of liquid metal has a rising character, this results in the Marangoni flow directed from periphery of the pool to its centre.

In this case the Lorentz force and surface tension gradient driven flows of liquid metal and heat sum together, and a deep and narrow weld is formed. If as a result of evaporation in the hottest central region of the pool the amount of surface-active elements is smaller than on the periphery, or if the flux contains no such elements, this will result in change of the direction of the Marangoni flow. In this case the Lorentz force and surface tension gradient driven flows of liquid metal and heat will have opposite directions, and the weld shape will be determined by the difference of these flows.

Therefore, the high penetrating power of the arc in TIG-F welding is provided by growth of the Lorentz force caused by the arc contraction and an increased current density at the anode. Surface-active elements that may transfer from flux to the weld pool, or the effect they may exert on the gradient of surface tension of molten metal, are not critical for the weld formation.

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SPECIFICS IN APPLICATION OF ALUMINIUM HIGH-STRENGTH ALLOYS FOR WELDED STRUCTURES

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Grades and general characteristic of weldability of new high-strength aluminium alloys, physical-metallurgical processes occurring in their welding, causes of porosity formation and measures for its prevention in weld metal during fusion welding, peculiarities of solidification of welds in multicomponent alloys, as well as formation of hot cracks and measures for their prevention, chemical and structural inhomogeneity are considered. Structural transformations leading to weakening of metal in the HAZ are analysed. Characteristics of new and improved methods and technologies for welding using the electric arc, electron beam and laser heat sources are presented.

Keyworks: *arc welding, aluminium, alloys, systems of alloying, microstructure, mechanical properties, weldability, porosity, hot cracks, strength of joints, aerospace engineering, transport systems*

Aluminium and its alloys occupy the second place after steel by production and consumption. Owing to the valuable complex of physical-mechanical, corrosion and technological properties the light alloys on aluminium base are used successfully not only in creation of vehicles, but also in other branches of industry (in civil engineering, military machinery, shipbuilding, manufacture of automotive and railway transport, electric engineering, in manufacture of cryogenic and chemical equipment, in agricultural and food machine building, etc.).

Most of products are manufactured from work-hardened semi-products of thickness from 0.8 to 50.0 mm using different methods of fusion welding. For this purpose, the new technological processes and equipment have been developed and implemented in industry, except well-known arc methods. Among these new methods there are plasma, pulsed-arc, flash-butt, EBW, laser welding and others. Each of these methods are used for making joints of different shapes, thickness and length.

Sphere of application of new and improved methods of welding is widened continuously. Thus, for example, EBW is used now not only in manufacture of small-sized parts and assemblies, but also in the manufacture of large products from aluminium semi-products up to 300 mm thickness. Laser-arc technologies are also mastered intensively. To strengthen the positions of aluminium in aircraft in future, the works are carried out rapidly in the improvement of technology of manufacture of semi-products and creation of new stronger Al–Li alloys, alloys of ultrahigh alloying and those being granulated. Coming from predictions, even at the beginning of the XXI century the volume of use of these alloys and composite materials on aluminium base in the design of airframe of aircrafts will amount to about 50 %.

The spreading of the above-mentioned materials in manufacture of critical products was due to the intensive investigation of weldability and development of effective measures for prevention of formation of hot cracks and pores in welds, and also for improvement of strength and reliability of welded joints. The fundamentals of metallurgical approach to the solution of problems of weldability by fusion of aluminium alloys were given in works [1–10].

Characteristic of weldability of some aluminium alloys. Aluminium and its alloys are divided by the method of producing into cast and wrought, and depending on application of hardening heat treatment — into hardened and non-hardened. Heat treatment includes usually quenching and subsequent natural or artificial ageing. Welding of intricate assemblies is performed most often after the complete cycle of heat treatment of prefabrications. In some cases the artificial ageing is made after welding that promotes the increase in strength of welded joints. The welded parts of a simple shape can be hardened by quenching and ageing. In this case it is possible to obtain the strength of welded joint equal to that of the parent metal.

Data about the chemical composition and properties of serial alloys of different grades, used in Russia and Ukraine, are given in GOST 4784–97 «Aluminium wrought alloys» and in handbooks [11, 12]. Compositions of alloys, used widely in aerospace industry, are given in Table 1. Strength of this group of alloys in sheets is varied within the wide ranges, namely from 430 up to 610 MPa. Many of them, for example, alloy V95, are very susceptible to the hot crack formation in fusion welding. The improvement of composition of alloy, similar to V96ts-3 of this system of alloying (Table 2), made it possible to increase the strength of shaped sections up to 760–780 MPa by adding of zirconium and other additions, however, the improvement of weldability of these alloys remains still actual.

New alloys 01570 (Al–Mg) and 01970 (Al–Zn–Mg) are the examples confirming the positive role of additions in the amount of 0.15–0.30 % Sc for the increase in strength of semi-products and upgrading of their weldability [14–16]. As-annealed alloy 01570 is close by the level of strength to heat-hardened al-

Table 1. Chemical composition of some high-strength aluminium alloys [2, 13]

Grade of alloy	Elements, wt.%											Other impurities (total), not more than, %
	Zn	Mg	Cu	Mn	Cr	Zr	Fe	Si	Li	Ti	Ni	
2024	–	1.50	4.40	0.60	–	–	0.50	0.50	–	–	–	–
D16	0.30	1.50	4.35	0.60	–	–	0.50	0.50	–	0.10	0.10	0.10
2124	–	1.50	4.10	0.60	–	–	0.30	0.20	–	–	–	–
1161	0.10	1.50	4.15	0.60	–	–	0.30	0.20	–	0.10	0.05	0.10
2324	–	1.50	4.10	0.60	–	–	0.12	0.10	–	–	–	–
1163	0.10	1.50	4.15	0.60	–	–	0.15	0.10	–	0.04	0.05	0.10
7079	4.30	3.30	0.60	0.20	0.175	–	0.40	0.30	–	–	–	0.10
7075	5.60	2.50	1.60	–	0.230	–	0.40	0.40	–	–	–	–
V95	6.00	2.30	1.70	0.40	0.170	–	0.50	0.50	–	–	0.10	0.10
7050	6.20	2.25	2.30	–	–	0.01	0.15	0.12	–	–	–	–
V95pch (increased purity)	5.75	2.30	1.70	0.40	0.170	–	0.15	0.10	–	0.05	0.10	0.10
7150	6.40	2.35	2.20	–	–	0.10	0.15	0.12	–	–	–	–
V95och (superpure)	5.75	2.30	1.70	0.40	0.170	–	0.10	0.10	–	0.05	0.10	0.10
7475	5.70	2.25	1.60	–	0.210	–	0.12	0.10	–	–	–	–
V93pch	6.90	1.90	1.00	0.10	–	–	0.30	0.10	–	0.10	–	0.10
7055	8.00	2.05	2.30	–	–	0.10	0.15	0.10	–	–	–	–
V96ts-3 (Zr-added)	8.10	2.00	1.70	0.05	0.050	0.15	0.20	0.10	–	0.05	–	0.10
Kh7093	9.00	2.50	1.50	–	–	0.10	0.15	0.12	–	–	0.20	–
V96Tspch	8.50	2.15	2.30	0.10	0.050	0.15	0.15	0.10	–	–	–	0.10
2090	–	–	2.70	–	–	0.10	0.12	0.10	2.20	–	–	–
2091	–	1.50	2.10	–	–	0.10	0.30	0.20	2.00	–	–	–
8090	–	0.90	1.30	–	–	0.10	0.30	0.20	2.40	–	–	–
1420	–	5.25	0.05	–	–	0.10	0.20	0.15	2.05	–	0.10	0.15
1424	–	3.20	–	–	–	0.10	0.30	0.10	1.80	–	–	0.20Sc
1441	–	0.90	1.70	–	–	0.10	0.30	0.10	1.90	–	–	–
1460	–	0.05	2.80	–	–	0.10	0.12	0.10	2.20	0.06	–	0.08Sc
2195	0.25	0.40	4.20	–	–	0.10	0.15	0.12	1.20	–	–	0.40Ag
01570	–	6.00	–	0.20	–	0.10	0.20	0.15	–	–	–	0.30Sc

Table 2. Mechanical properties of high-strength pressed and rolled semi-products from alloy of Al–Zn–Mg–Cu system [2, 3]

Grade of alloy	Type of semi-product	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	K_c^{cond}, MPa$\sqrt{m}$	LCF, cycle	SCCF, MPa
1973 T2	Shaped section	580	550	12	130	220	147
	Plate	560	520	10	124	220	147
	Sheet	560	520	10	112	220	–
V95och T2	Shaped section	560	510	12	130	200	172
	Plate	540	490	11	124	160	172
	Sheet	540	490	11	112	160	–
V96ts-3 T2	Panel	610	580	10	109	200	167
T12	Shaped section	660	630	10	109	–	117
V96ts-1 T2	Same	670	620	8	57	200	167

Note. Here, K_c^{cond} — conditional index of fracture toughness; LCF — low-cycle fatigue (number of cycles before fracture in testing samples with a stress raiser K_t = 2.6 at σ = 160 MPa); SCCF — factor of stress corrosion cracking.

Table 3. Comparative analysis of mechanical tests of 3 mm thick sheets and welded joints from alloys 01570 (Sc) and AMg6

Grade of alloy	Parent metal			Welded joint		
	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	Filler wire	σ_t, MPa	Angle of bending, deg
01570	421.4	313.6	20	1571	398.0	140
AMg6	343.0	166.6	25	Sv-AMg6	336.1	140

Table 4. Effect of scandium on mechanical properties of shaped sections from experimental alloys Al–Zn–Mg–Cu in as-heat-treated state using condition T6

Experimental alloy	Elements, wt.%						Mechanical properties		
	Zn	Mg	Cu	Mn	Zr	Sc	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %
1	8.8	2.7	2.4	0.20	0.18	–	728	649	8.9
2	8.9	2.6	2.4	0.19	0.15	0.31	763	690	8.4

loys. Sheets have ultimate strength of about 420 MPa, elongation — 20 %. Strength factor K_{str} of welded joints is 0.85–0.95. By these characteristics the alloy is much superior to the similar alloy AMg6 without scandium (Table 3).

Alloy 01970 is characterized by the higher level of strength among the well-known weldable aluminium alloys. Sheets after artificial ageing have 520 MPa ultimate strength, 480 MPa yield strength, 12 % elongation, K_{1c} is 97 MPa$\sqrt{m}$. Both alloys possess a good weldability. Ultimate strength of welded joints of sheets from alloy 01970 after artificial ageing during 1 month reaches 420 MPa, bending angle is 8°, impact strength of weld metal is 23 J / cm^2. They have high stress corrosion resistance.

It should be noted that the positive effect of scandium on strength of semi-products is also observed in high-alloy alloys of Al–Zn–Mg–Cu system (Table 4).

Al–Li alloys represent a special group of alloys due to the presence of alkali metal in their composition, which imparts specific properties to the semi-products [16, 17]. For example, their specific mass is abruptly decreased, while the modulus of elasticity and specific modulus are also abruptly increased with increase in the amount of lithium in the alloy. It is this circumstance that attracts attention of designers of the new machinery, in particular vehicles, to these alloys.

All the alloys of this group (see Table 1) are heat-hardened and characterized by a comparatively high level of mechanical properties. Three series of alloys of different systems of alloying, given in Table 5, are differed from other Al–Li alloys by the feasibility to provide a satisfactory welding [18].

As to the susceptibility to hot crack formation in welds, they are arranged, by the order of increasing this index, as follows: 1420, 1460, 1440. The level of material weakening in welding is lower in alloys of series 1420 and higher — in alloys 1440. Consequently, welding of complex-alloyed alloys of series 1440 should be made preferably at minimum heat input using electron beam or laser methods.

Alloy 1420 of Al–Mg–Li system has a specific mass which is by 12 % lower, and the modulus of elasticity is by 8 % higher than that of duralumin D16 used in aircraft industry. Alloy is characterized by the high corrosion resistance, that is proved by a successful experience in service of vertical take-off aircrafts, made from this alloy, which have a launching base on sea ships starting from the 1970s [4].

A large assortment of sheets has been produced from alloy 1420, including those for superplastic forming. Sheets have strength, yield strength and elongation, close to the mentioned parameters of duralumins, and a very low rate of a fatigue crack propagation. This characteristic is very important for aircraft structures designed by the principle of a safe damage. Resistance to repeated loads, i.e. low-cycle fatigue, in alloy 1420 is lower than that in duralumins.

Modification of alloys, such as 1421 and 1423 [18], alloyed additionally with scandium, have higher values of ultimate strength and yield strength than the basic alloy 1420. The new modification of alloy 1424 of Al–Mg–Li–Zr–Sc system is characterized by a lower content of lithium, higher corrosion resistance, good weldability. Alloy is challenging for use in manufacture of welded shells of fuselages in advanced aircrafts.

Table 5. Typical mechanical properties of parent metal and welded joints of sheets from Al–Li alloys [2, 5, 23] in argon arc welding

Grade of alloy	System of alloying	Sheets			σ_t^{WJ}, MPa	K_{str}^{WJ}
		σ_t, Ì Pà	$\sigma_{0.2}$, Ì Pà	δ, %		
1420	Al–Mg–Li	454	330	14.5	310 / 280	0.70 / 0.62
1424		480	360	16.0	320 / 280	0.66 / 0.58
1440	Al–Cu–Mg–Li	480	400	17.6	282 / 262	0.58 / 0.55
1441		435	340	14.0	280 / 285	0.64 / 0.65
1460	Al–Cu–Li	525	457	8.0	295 / 249	0.56 / 0.47
1464		550	500	10.0	300 / 270	0.55 / 0.49

Notes. 1. Samples of parent metal were cut along direction of rolling. 2. For welded joints the numerator gives values for weld metal with upper bead, denominator gives values for metal of cleaned welds (without beads).

Table 6. Susceptibility to hot crack formation in welding of Al–Li alloys using different fillers

Grade of alloy	*Type of filler*	*À, %*
1420	Without filler	44.5
	1420	32.0
	Sv-AMg63	17.0
	Al–6Mg–0.5Sc	5.0
1460	Without filler	60.0
	Sv-AMg63	54.0
	Sv-1201	50.0
	Al–10Cu–0.5Sc	15.0

Alloys of series 1440 of Al–Cu–Mg–Li system, close by the chemical composition, are characterized by a good combination of characteristics of strength and safe service [4, 19]. Owing to the optimum ratio of main alloying components, the alloy 1441 is suitable for manufacture of thin plated sheets using the method of a coil rolling. It preserves the properties of a quick-hardened state for the longer period than the conventional duralumin D16 (up to 10–15 h). Sheets of alloy 1441 are differed from duralumin by a smaller (by 7 %) specific mass and higher values of low-cycle fatigue (by 50 %) and rate of fatigue crack propagation (by 30 %). Alloy is used in manufacture of fuselages of military aircrafts, including amphibians [4, 20].

In welding without fillers, the alloys 1440 and 1441 are characterized by an increased susceptibility to hot crack formation A = 65 % [21]. Resistance of weld metal against the hot cracking can be improved by using filler wire Sv-AMg63 (A = 24 %). In this case the strength of 6.5 mm thick joints is 280 MPa, angle of bending is 50°, impact strength of weld metal is 14 J / cm^2. It should be recognized that the alloys of 1440 series are not recommended for a wide application in welded structures using conventional arc methods of welding. The feasibility of improving their characteristics of weldability is supposed in EBW or laser welding with use of special filler materials.

Alloys of 1460 series refer to the Al–Cu–Li system with additions of zirconium and scandium. They are most high-strength weldable heat-hardened alloys of the Al–Li group [2–4]. Values of strength of parent metal are at the level of 540–600 MPa, that provides at 2.6 g / cm^3 density and 80 MPa modulus of elasticity the reduction in structure mass by 15–20 % in case of replacement of other alloys. This alloy is specific by a simultaneous increase in strength and ductility at cryogenic temperatures. This makes it promising for use in welded cryogenic tanks. Modifications of alloy 1464 are differed from a basic composition by the presence of a complex of modifiers (up to 0.15 %) that improves the mechanical properties of semi-products and welded joints (see Table 5).

Welded joints of 1460 alloy, as also other heat-hardened weldable alloys, have lower (60–80 %) values of strength than those of parent metal, that depends on postweld heat treatment of joint and on the technology of welding itself [5, 22]. In use of conventional fillers Sv-1201 or Sv-AMg6 the weld metal shows a susceptibility to the hot crack formation. Application of the higher-alloy filler wire Sv-1217 (Al + 10 % Cu) leads to the significant change in chemical composition of weld, its mechanical and technological properties. With increase in copper content in weld up to 7–8 %, the strength of joints is increased simultaneously and the weld metal resistance to hot cracking in welding is also improved. Additions of scandium (0.5 %) and zirconium (0.3 %) in the filler of Sv-1201 or Sv-AMg6 type promote the increase in resistance to hot cracking in welding and the improvement of mechanical properties of the joints (Table 6).

Measures for prevention of formation of oxide film inclusions in weld metal during fusion welding. Oxide inclusions in weld metal are the most widely spread defect of aluminium alloy welded joints. They reduce significantly the static and dynamic strength, disturb the tightness of structures. Specifics and kinetics of interaction of components of aluminium alloys with gases of surrounding medium are described in manuscripts [9, 10]. Amount and sizes of inclusions in weld metal depend on thickness and phase composition of surface oxide film forming on parts before or in the process of welding.

Oxidation of new aluminium alloys 1201 (Al–Cu), 1420 (Al–Mg–Li), 1460 and 1461 (Al–Cu–Li) in heating from 200 up to 550 °C in air and in argon was studied [23, 24]. The lowest rate of oxidation was observed for alloy 1201. Alloy AMg6 is oxidized by the law, which is close to linear. The same relation, but at the higher absolute changes in mass of samples, was recorded for alloys 1460 and 1461. The linear law of oxidation for alloy 1420 is manifested up to 400–420 °C temperature. Then, the abrupt increase in rate of alloy oxidation is occurred and it is 3–10 times increased at 450–500 °C.

In welding of Al–Li alloys, in particular alloy 1460, the extended (sometimes continuous) inclusions of oxide film are formed, oriented along the weld and arranged in the upper middle part of the weld section.

As the investigations [25, 26] showed, the recommended measures for prevention of formation of inclusions in arc welding using filler of different aluminium alloys were not sufficient for alloys with lithium and copper. It was necessary to create the more favourable conditions for destroying oxide films available at the filler wire surface and prevention of oxidation of molten metal in weld pool.

The radical method was the wire preheating to 150–200 °C directly in the process of welding by passing the current at the area of up to 100 mm length. In this case the cooling of weld pool area at the site of filler feeding is prevented, temperature is increased and equalized over the entire surface, processes of dehydration and cathode destroying of oxide films at the surfaces of wire and weld pool are more intensive and the formation of oxides becomes hardly probable from the thermodynamic point of view. Under these conditions the welds, free of oxide inclusions, were produced (Figure 1).

Causes and measures of prevention of porosity in weld metal. The main cause of porosity is considered to be hydrogen, and, more clearly, its jump-like decrease of solubility in weld metal during solidification (crystallization) [9, 10], which is proved by comparatively small pores arranged in weld metal along the boundaries of a layer-by-layer crystallization.

Another situation is observed with large pores, which are not associated more often with layers of crystallization, but located either in the upper part of weld, or in the fusion zone. The appearance of this porosity is usually a result of serious violations of optimum conditions of welding including preparation of parent metal and welding wires [27], and also high content of gases in the metal being welded [28].

Specifics and mechanism of formation of porosity in welding of Al–Li alloys were studied in numerous works [29, 30]. It follows from the analysis of these works that a thick and porous oxide film, which is capable to adsorb a large amount of moisture, is formed at the surface of semi-products. At different stages of production of semi-products the chemical compounds of lithium of type of hydrides and hydrocarbonates may appear in their surface layers [28]. The most probable places of their formation are the precipitations of secondary phases with a high content of lithium at the grain boundaries. Therefore, the compounds of hydrides and others penetrate for a large depth, and the near-surface layers are depleted with metal lithium. During heating in welding they evolve the gas bubbles, which are formed not only in weld pool, but also in metal, heated up to solid-liquid state in the HAZ. Sometimes they cause the metal buckling in a near-weld zone at the reverse side of the joint. In the upper part of the joint the pores are formed seldom in the near-surface layer, and their size is much smaller than that in a root part. This is due to the gas bubbles escape to the surface until complete solidification of the pool.

In argon-arc welding of joints using a technological backing, having a forming groove, the metal has usually a through penetration. During heating and metal melting the stage of formation and enlargement of gas bubbles in the fusion zone is transferred into the stage of weld pool degassing. This process was observed visually in the form of gas bubbles escape to the pool surface where they interrupt their existence.

The smaller bubbles, formed in the lower part of the weld pool, have no time to escape to the surface due to a low rate of their lifting. Negligible metal movement in this part of the pool contributes also to the capture of gas bubbles by the crystallizing metal, resulting in the pore formation. It is difficult to eliminate this porosity even at multiple remelting of the weld. They can be removed only after repeated melting of metal from the weld root side.

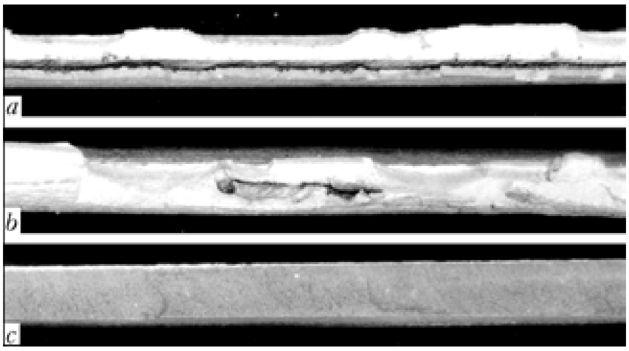

Figure 1. Longitudinal fractures of welds with inclusions of oxide films at conventional argon-arc welding with tungsten electrode (*a*, *b*) and welds free from inclusions in welding with preheating of filler wire (*c*); sheets from Al–Li alloy 1460 of 3 mm thickness, filler Sv-1201 1.6 mm diameter (×3)

It is possible almost completely to prevent the appearance of large pores both in the upper and also in the lower part of weld by removal of metal surface layer of 0.2–0.3 mm thickness. It cannot be recognized that decrease in porosity in such away is effective from the technical-economic point of view.

At present, the method of welding has been developed which does not require mechanical or thermovacuum treatment of sheets. Owing to the intensive electromagnetic action of scanning or pulsating arc of alternating asymmetric current on the weld pool, the entire volume of the latter is stirring. Here, the gas bubbles are detached easily from the melted metal surface and forced out by the molten metal flows to the pool surface [30]. The pulsed-arc welding at conventional edge preparation and more effective protection of the welding zone by argon contributes greatly to the prevention of appearance of a pronounced porosity.

Specifics of crystallization of welds, measures of prevention of hot crack formation in welding. It was established by now that hot cracks in fusion welding of aluminium alloys are formed and spread at the final stage of weld crystallization and have an intercrystalline nature [9, 10, 31]. Owing to the periodicity of weld crystallization, the hot cracks can be initiated and arrested within one or several layers of crystallization.

In some cases, associated with unfavourable selection of the filler metal, the hot cracks are appeared in near-weld zone (Figure 2, *b*), because it is the zone of «weakness» where the fusible phases from the parent metal are clustered. It is assumed that this large avelange crack can propagate also into the zone of the solidified metal.

Dependence of susceptibility to crack formation on chemical composition of alloys and conditions of welding is described in works [32, 33]. Non-uniformity of distribution of silicon and iron impurities among the structural constituents of weld metal and fusion zone is observed in many aluminium alloys. Here, the eutectics of a complex composition are formed which are more fusible than those in alloy of high purity by impurities. This leads to widening the temperature

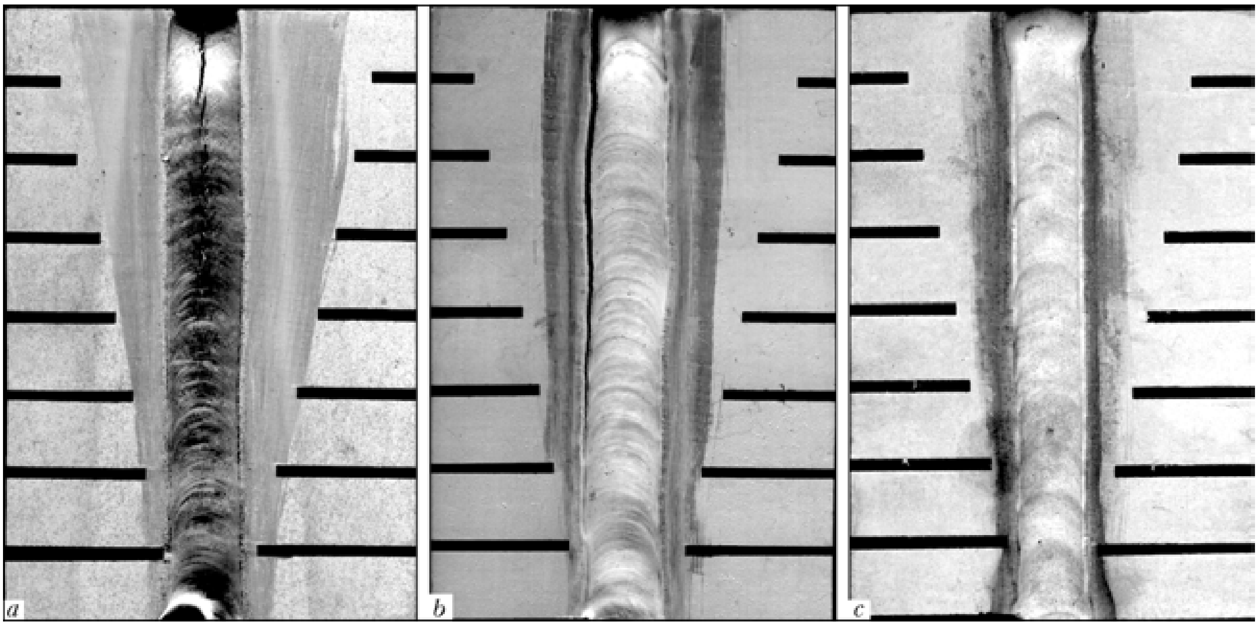

Figure 2. Main types of hot cracking of welds: *a* — conventional in weld center; *b* –– along the fusion boundary of parent metal and weld, can enter the zone of overheated parent metal; *c* –– without visible cracks

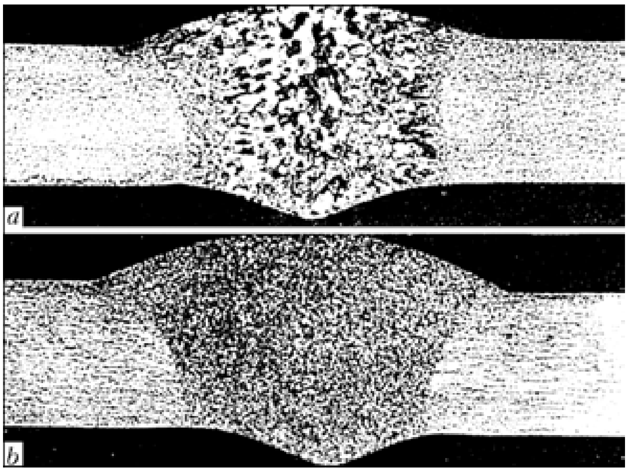

Figure 3. Macrosections of welded joints obtained by argon-arc welding with non-consumable electrode of 1420 alloy sheets of 4 mm thickness using fillers Sv-AMg6 without zirconium (*a*) and Sv-AMg63 with zirconium (*b*) (×6)

interval of crystallization by reduction in temperature of non-equilibrium solidus and, as a consequence, to the increase in weld metal susceptibility to hot crack formation. For example, in alloy 1201 (Al + 6 % Cu) the hot-shortness index, from the results of testing Houldcroft samples, decreased from 38 down to 19 % (two times) with decrease in amount of impurities of iron and silicon from 0.2–0.3 % to 0.03–0.05 % (Table 7). Results of systematic investigations made the amount of inevitable impurities of silicon and iron to be limited to 0.05–0.10 % to improve the weldability and mechanical properties of joints of high-strength alloys of different systems of alloying on the base of aluminium.

Susceptibility to cracking in fusion welding of high-strength aluminium alloys can be reduced by creation of fine-crystalline structure of welds, for example, by using a pulsating or scanning arc [34], filler wires with a high content of main alloying components (magnesium, copper, silicon) [33, 35] or effective modifiers, such as scandium, zirconium, titanium and others [36].

The example of effective refining of structure of welds is the use of filler wire Sv-AMg63, containing, except titanium, also up to 0.3 % Zr,in welding many alloys (Figure 3). At present, the filler materials of different systems of alloying (Al–Mg, Al–Cu, Al–Cu–Mg) with addition of 0.3–0.6 % Sc, which is the most effective modifier of crystalline structure of welds, have been developed.

Table 7. Dependence of susceptibility to hot cracking in welds and mechanical properties of high-strength aluminium alloys of different systems of alloying on content of impurities

Grade of alloy (alloying)	*Impurities, wt.%*		*À, %*	*Ultimate strength σ_t, MPa*	*Ductility α, deg*	*Impact strength $\grave{a}_n$, J/cm^2*
	Fe	*Si*				
1201 (Al6CuMn)	0.05	0.03	19	454 / 298	65 / 78	21 / 20
	0.22	0.18	38	446 / 299	46 / 56	14 / 11
1160 (Al4.5Cu1.5Mg)	0.05	0.04	37	492 / 362	42 / 64	20 / 16
	0.25	0.20	58	485 / 339	26 / 48	15 / 10

Note. The numerator gives data for semi-products, denominator gives data for welded joints.

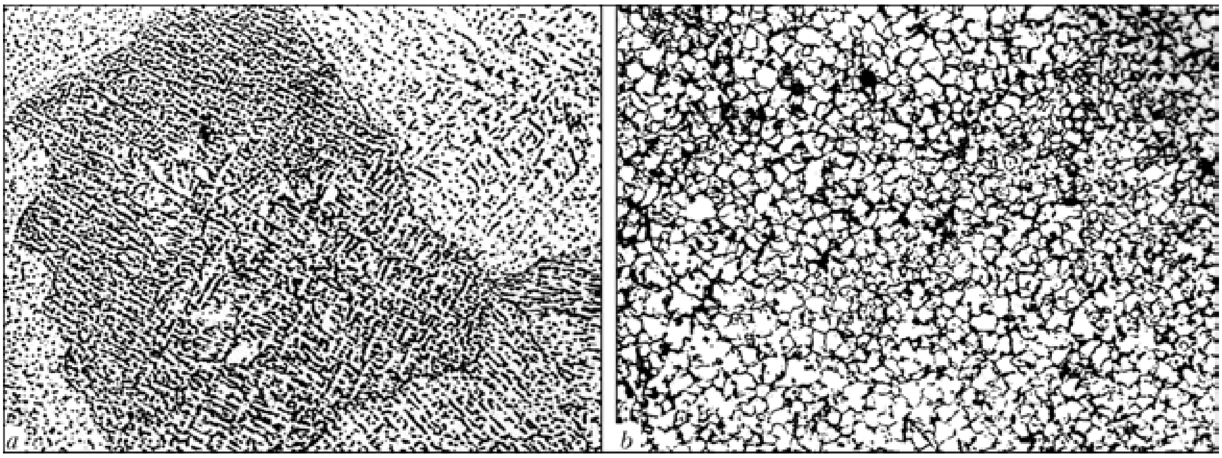

Figure 4. Microstructure of weld metal in fusion of alloys of Al–6Zn–2Mg–0.14Zr system without fillers: *a* — coarse-crystalline dendritic microstructure in alloy without modifiers; *b* — fine-crystalline subdendritic microstructure in alloy with additions of modifiers 0.15 % Zr and 0.35 % Sc (×500)

As is seen from Figure 4, the application of these fillers in welding alloy Al–6Zn–2Mg provides transition of weld structure from coarse-crystalline dendritic structure (Figure 4, *a*) to fine-crystalline subdendritic structure (Figure 4, *b*) with a size of cells up to 20–30 μm (degree of refining by one order). These structures of weld contribute not only to the improvement of its mechanical properties, but also to a good resistance to hot crack formation (Figure 5). In accordance with results of welding of Houldcroft samples (see Figure 2) the hot-shortness index of welds in welding alloy V95 using filler from alloy AL–6Mg–0.5Sc is varied from 0 to 15 %, that 3–4

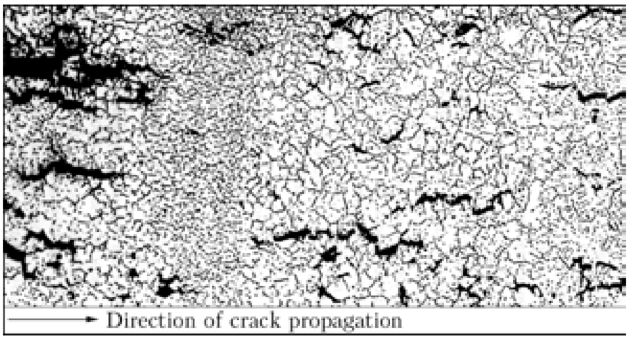

Figure 5. Microstructure of weld metal with scandium (subdendritic structure with non-propagating microcracks) (×100)

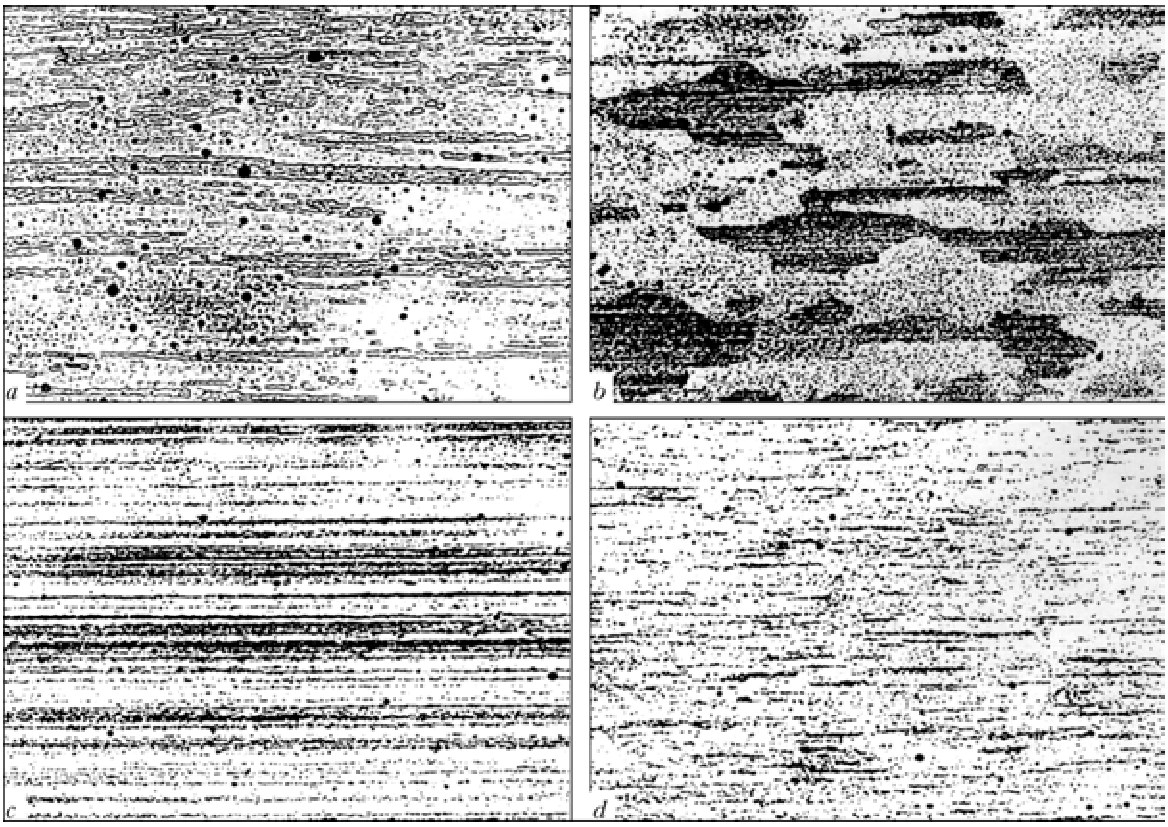

Figure 6. Microstructure of cold-rolled sheets of two alloys of Al–8Zn–2.1Mg–1.9Cu–0.11Zr (*a, b*) without scandium and with scandium and Al–8Zn–2.1Mg–1.9Cu–0.11Zr–0.12Sc (*c, d*) in initial state (*a, c*) and after heating up to 500 °C during 30 min (*b, d*) which caused recrystallization in alloy without scandium (*b*) (×156)

times lower as compared with a basic variant of filler without scandium.

The positive role of scandium which is added in the amount of 0.1--0.2 % to the parent metal should be noted. The presence of scandium gives an opportunity to prevent the formation of a pronounced structural inhomogeneity in HAZ during welding, that occurs usually due to recrystallization and concurrent processes along the boundaries in work-hardened semi-products without scandium (Figure 6).

Structural transformations and metal weakening in HAZ during welding. Semi-products from high-strength aluminium alloys are subjected to weakening in a near-weld zone under the action of welding heating. Here, the cold working is lost completely, while the heat hardening can be recovered [37]. Different methods of welding are located at different levels of scale in the range from $1\cdot10^3$ to $1\cdot10^7$ W / cm^2 [38] by density of energy and, consequently, also by the degree of thermal effect on the material being welded (inverse relationship).

As to the change of mechanical properties of the material, its hardness and strength, then it depends on the specifics of structural transformations in alloys of different systems of alloying. As is seen from Figure 7, there are no dips in curves of hardness change in welded joints of alloy 1420 in those places, where other heat-hardened alloys are weakened greatly due to overageing and partial annealing. It can be supposed that the recovery to a hardened state is occurred in this alloy at the entire area of effective thermal action. This creates conditions for hardness recovery at the entire length of HAZ at repeated artificial ageing of the parent metal in the welded joint. This

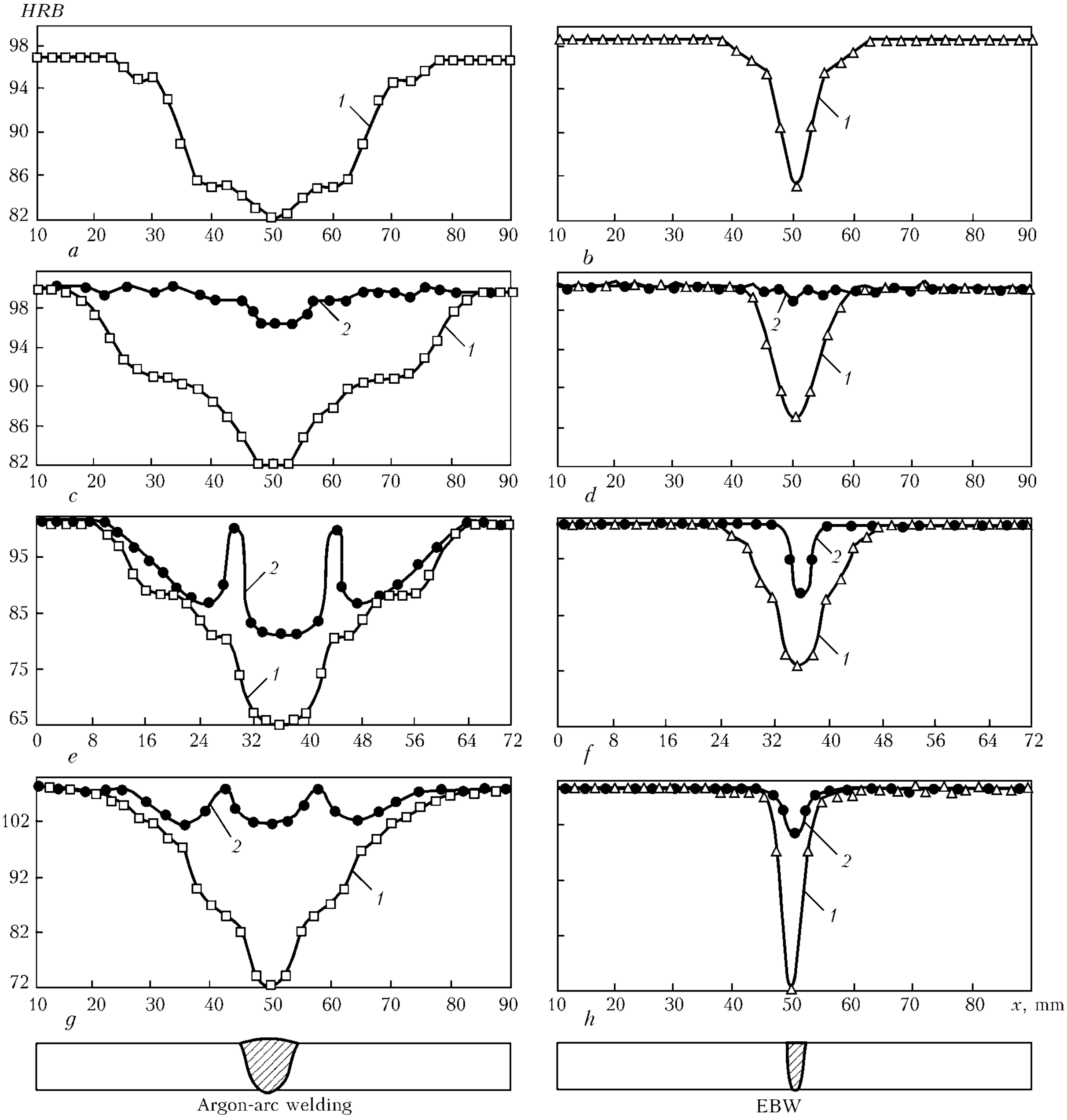

Figure 7. Curves of change in hardness of metal of welded joints in argon-arc welding (*a, c, e, g*) and EBW (*b, d, f, h*) of aluminium alloys AMg6NPP (*a, b*), 1420 (*b, d*), 1201 (*e, f*), 1460 (*g, h*): *1* — state directly after welding using, respectively, arc (❐) and electron beam (Δ) methods; *2* — state after artificial ageing of joints produced by both methods

Table 8. Comparative properties of aluminium alloys and their welded joints (for cryogenic tanks of rockets) [1, 2]

Grade of alloy (condition)	T_{test}, *K*	σ_t, *MPa*	$\sigma_{0.2}$, *MPa*	δ, %	*KCV*, *J/cm*^{2}
AMg6 (cold working 20 %)	293	420 / 296	252	15.0	22 / 16
	77	520 / 400	292	34.5	20 / 16
	20	590 / 420	325	14.0	15 / 10
1201 (heat hardening)	293	420 / 280	325	9.5	12 / 17.5
	77	420 / 355	325	12.0	12 / 14.5
	20	610 / 405	440	15.0	14 / 14.8
1460 (heat hardening)	293	530 / 290	495	10.0	11 / 10
	77	615 / 355	325	17.5	13 / 7
	20	760 / 385	560	13.5	15 / 6

Note. The numerator gives values σ_t and *KCV* for parent metal and denominator gives values for argon-arc welded joints.

feature of transformations in alloy 1420 is stipulated, probably, by specific single-stage mechanism of precipitation of hardening phase that gives an opportunity to obtain high values of ultimate strength of welded joint (approximately 400 MPa).

The low duration of action of welding cycle temperatures defines the specifics of transformations as compared with isothermal conditions of heating. Under these temperature-time conditions, a partial recovery of aged alloy to the hardened state and subsequent its hardening at artificial ageing of joints is possible [1]. Welding short-time heating to temperatures below 300 °C does not almost change the structure and hardness of alloys.

To predict the changes in hardness and strength of HAZ metal, the thermokinetic diagrams of weakening of alloys 1201, 1420 and 1460 in heating under isothermal conditions have been developed [39–41].

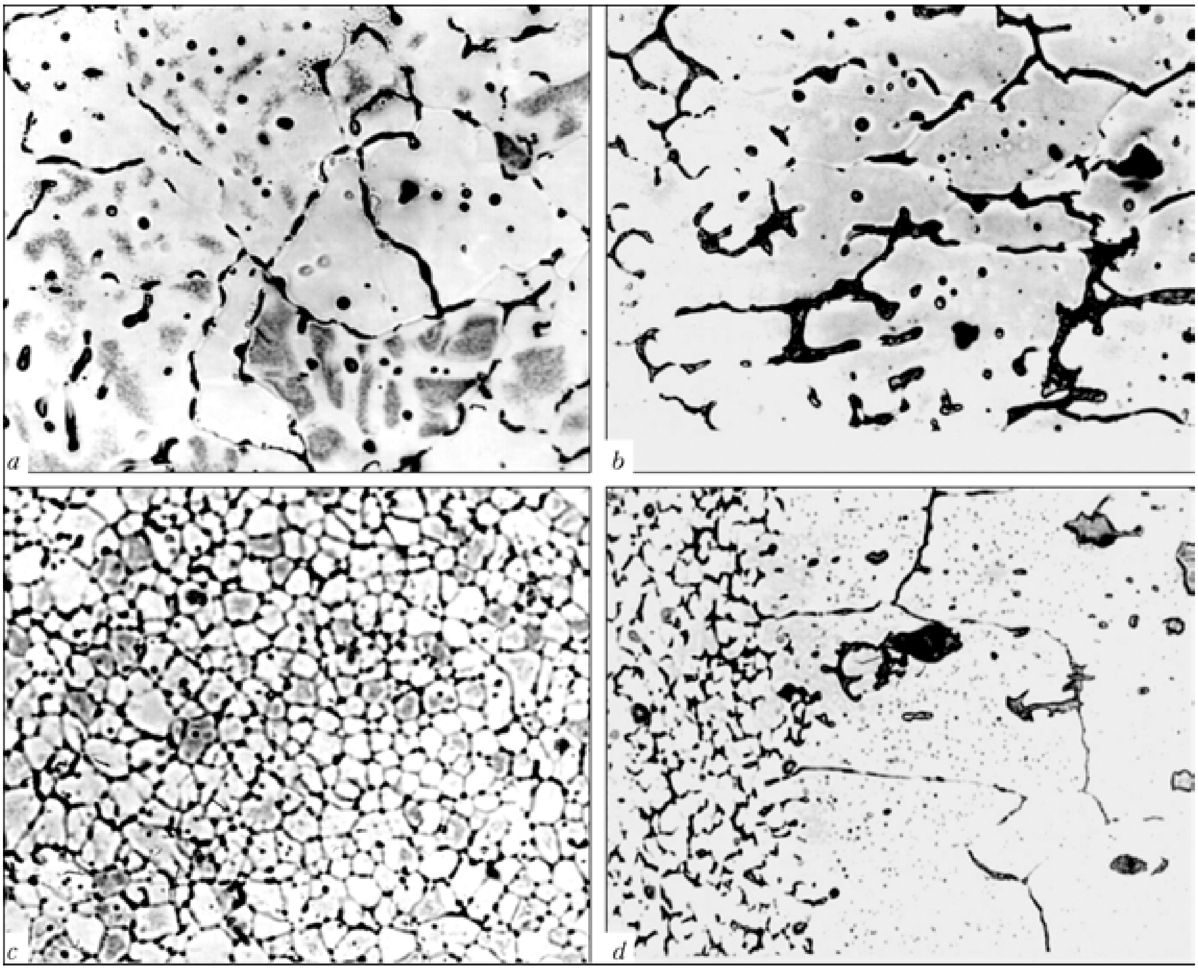

Figure 8. Microstructure of weld metal (*a*, *c*) and zone of weld fusion with parent metal (*b*, *d*) of sheets from alloy 1201 of 6 mm thickness without filler in argon-arc welding (*a*, *b*) and EBW (*c*, *d*) (×500)

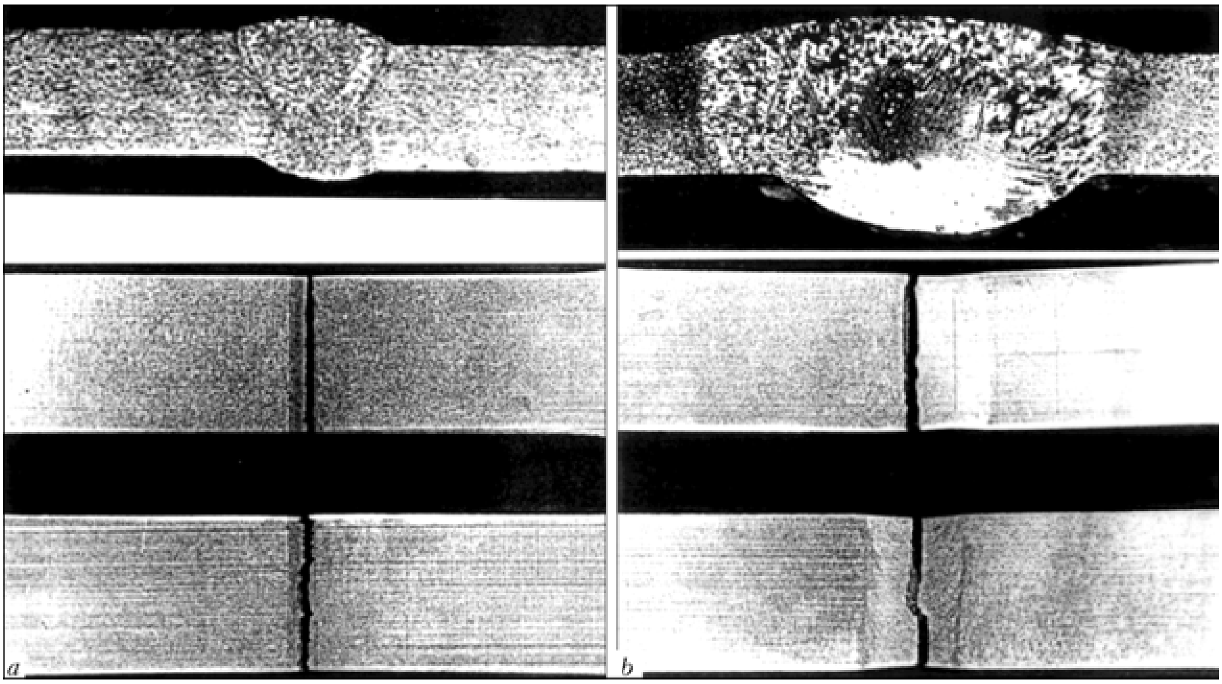

Figure 9. Macrostructure of welded joints of alloy 1420 and types of fracture of samples in tension (along the fusion zone and weld): *a* — laser welding, σ_t = 360–380 MPa; *b* — argon-arc welding, σ_t = 300–330 MPa (×5)

The higher thermal stability of alloy 1420 as compared with 1201 and 1460 is noted. Owing to this, the welded joints of alloy 1420 have the higher level of strength of metal both in weld and also in HAZ.

The real pattern of changing the physical-mechanical properties of some alloys being considered in argon-arc welding and EBW is given in Figure 7. As to different temperature conditions of service, including cryogenic, the values of main characteristics of mechanical properties are given in Table 8. They show that it is rational to manufacture the challenging tanks of rockets for liquid hydrogen and other products of cryogenic engineering, operating at low temperatures (4.2–77 K), from alloys 1201 and 1460.

As the metallographic examinations showed (Figure 8), the fracture of metal of weld and near-weld zones occurs due to change in initial structure of semi-products. Coarse-crystalline structure of welds, growth of grains of the parent metal and formation of coarse intergrain layers from fusible phases are observed noticeably in argon-arc welding (Figure 8, *a*, *b*). In EBW and, possibly, in laser welding (Figure 8, *c*, *d*) these changes are expressed to a smaller extent, thus providing the high level of welded joint characteristics being examined (Figure 9).

Thus, the results of investigations and developments confirm the creation of unique compositions of complex-alloyed aluminium alloys and analogues of known alloys of different systems of alloying with microadditions of effective modifying elements of scandium and zirconium, which are characterized by higher characteristics of adaptability to manufacture and strength. Their weldability by fusion using the advanced technologies is characterized as good or satisfactory, and the rupture ultimate strength of heat-hardened deformed semi-products reaches 750 MPa.

Among the challenging systems of complex alloying, the alloys Al–Zn–Mg–Cu and Al–Cu–Mg–Li with microadditions of elements of the transition group should be recognized as the base of the new higher-strength weldable alloys. Having the satisfactory characteristics of weldability, they will promote the progress in the development of structures of many new products of transport purpose, such as airbuses, high-speed train cars, products of defence industry, that will increase the technical and economic characteristics of their manufacture and service.

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DEVELOPMENT OF FILLER METALS FOR BRAZING HEAT-RESISTANT NICKEL- AND TITANIUM-BASE ALLOYS

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Fundamental studies of alloys of the Ni–Cr–Zr and Ti–Zr–Mn systems have been conducted to investigate the content of elements showing promise in terms of development of brazing filler metals. The data on melting points of the alloys, their phase composition and morphological peculiarities have been obtained. Brazing filler metals have been developed on the basis of the investigation results for brazing high heat-resistant nickel alloys and intermetallic alloy γ-TiAl. Structure and properties of brazed joints have been studied.

K e y w o r d s : *high heat-resistant nickel alloy, eutectic, solid solution, carbides, strengthening, lamellar structure, γ′-phase, arc brazing, vacuum brazing, heat treatment*

Among numerous commercially available heat-resistant alloys the alloys used for the manufacture of components of the hot section of gas turbine engines, and turbine blades in particular, attract the highest attention. In the majority of cases these are the high nickel alloys. Large investments have been made recently to improve these alloys. Development of dispersion-strengthened, single-crystal and eutectic alloys, as well as Re-doped alloys [1], opened up wide prospects for upgrading of engines. For example, the Re-containing alloys made it possible to increase the temperature of gas ahead of the turbine to 2000–2200 K.

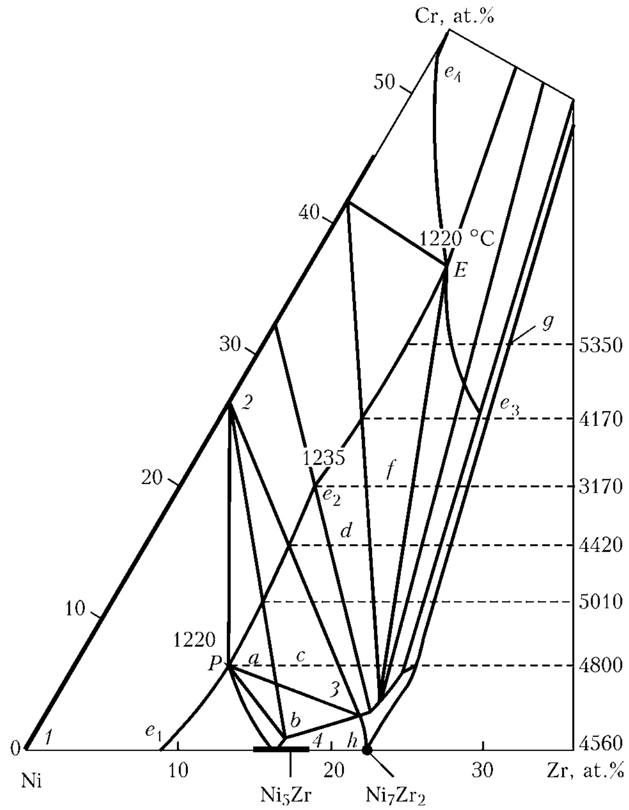

Figure 1. Projections of solidus and liquidus surfaces of nickel angle of constitutional diagram of the Ni–Cr–Ni_7Zr_2 system (structural components: *a* — L + γ + Ni_5Zr; *b* — *L* + Ni_5Zr + Ni_7Zr_2; *c* — γ + $ZrNi_5$ + Ni_7Zr_2; *d* — γ + Ni_7Zr_2; *f* — α + γ + Ni_7Zr_2; *g* — α + Ni_7Zr_2; *h* — Ni_5Zr + Ni_7Zr_2) see the rest of the designations in the text

Studies showing favourable results are in progress now on alternative alloys, such as those based on intermetallics, among which the most promising alloy is γ-TiAl [2].

However, problems associated with making permanent joints in such alloys for the manufacture of components of the hot section of gas turbine engines, as well as repair, remain unsolved as yet. This can be explained by the fact that welding is inapplicable for joining these materials, while brazing is still based on old ideas, which, being productive in the past, no longer meet requirements of the present.

Most researchers employ nickel filler metals for brazing high alloys, wherein silicon and boron are used as depressants. It is our opinion that Ni-base filler metals, containing titanium, zirconium, hafnium, niobium, etc. used as depressants, show more promise. And it is the purpose of this study to substantiate this postulate. Studies [3–5] describe earlier research on these alloys conducted by the E.O. Paton Electric Welding Institute and G.M. Kurdyumov Institute of Metal Physics.

Consider peculiarities of these alloys by an example of the Ni–Cr–Zr system. Figure 1 shows projections of solidus and liquidus surfaces in a region of the Ni–Cr–Zr constitutional diagram corresponding to alloys with a high nickel content, and, separately, projections of points of microhardness of eutectics (*HV*, MPa). The constitutional diagram is based on the results of investigations of cast alloys by the metallography, X-ray diffraction and differential thermal analysis methods. It reflects the phase composition of alloys with a different mass fraction of chromium and zirconium. As follows from Figure 1, the constitutional diagram of the Ni–Cr–Zr system has two quasi-binary sections in a region confined by triangle Ni–Cr–Ni_7Zr_2, within two-phase regions γ-Ni + Ni_7Zr_2 and α-Cr + Ni_7Zr_2. And it is these sections that determine the character of phase equilibria in this region of the diagram. They can be shown in the concentration triangle as rays passing through the points with coordinates $Ni_{68}Cr_{32}$–$Ni_{76}Zr_{24}$ and Cr–$Ni_{67.5}Zr_{23.5}$. Both sections are of the eutectic type. Eutectic between γ-Ni and Ni_7Zr_2 contains about 8.8 at.% Zr and 20 at.% Cr, and has a melting point of 1235 °C (Figures 1 and 2).

There is a region of four-phase peritectic equilibrium in the constitutional diagram, which in Figure 1 is confined by points *2–3–4–P*. Alloys the composition of which falls within a region confined by points *2–3–4* are characterised by the solidification that is completed with reaction $Ni_7Zr_2 + L = \gamma\text{-Ni} + Ni_5Zr$ under equilibrium conditions at a temperature of 1220 °C. These alloys are the three-phase ones and consist of γ-Ni, Ni_5Zr and Ni_7Zr_2. Alloys in a region of the constitutional diagram confined by points *1–2–4* should be the two-phase ones and consist of γ-Ni and Ni_5Zr.

Eutectic alloys containing 8.8 at.% Zr are of the highest interest in terms of development of brazing filler metals. Figure 3 shows variations in melting points and structural states of such alloys depending upon the chromium content. It should be noted that alloying of binary eutectic Ni + Ni_5Zr with chromium leads only to an insignificant increase in solidus temperature, but causes a substantial change in microhardness of the eutectic component of alloys with a constant (8.8 at.%) zirconium content. Thus, within the γ-Ni + Ni_5Zr binary region an increase in mass fraction of chromium in the alloys leads to increase in mocrohardness of the eutectic due to hardening of γ-Ni solid solution. With formation of intermetallic Ni_7Zr_2, the microhardness of which is much lower than that of γ-Ni, and which contains more than 25 wt.% Cr, as well as Ni_5Zr in structure of the alloys, the microhardness of the eutectic starts falling and reaches minimum in the $Ni_{68}Cr_{32}$–Ni_7Zr_2 section. Further increase in mass fraction of chromium leads to formation in the alloys of a ternary eutectic (point *E* in Figure 1), containing hardened α′-Cr with a high mass fraction of nickel, while after intersection with line e_4–e_3 it leads to formation of the primary crystals of α′-Cr, the presence of which in structure of the alloys causes increase in hardness.

Considered below will be structure and chemical heterogeneity of brazed seams produced by using filler metals based on Ni–Cr–Zr system under the arc heating conditions. As is well known, one of the main differences between brazing and welding is that in the latter case the filler metal is close as a rule in structure and properties to the base metal. However, it is impossible to use a matching filler for welding high heat-resistant nickel alloys with a high content of the γ′-phase (e.g. JS6U, JS32, ChS70, ChS88, IN 738, etc.). In this case the use is made of the alloys

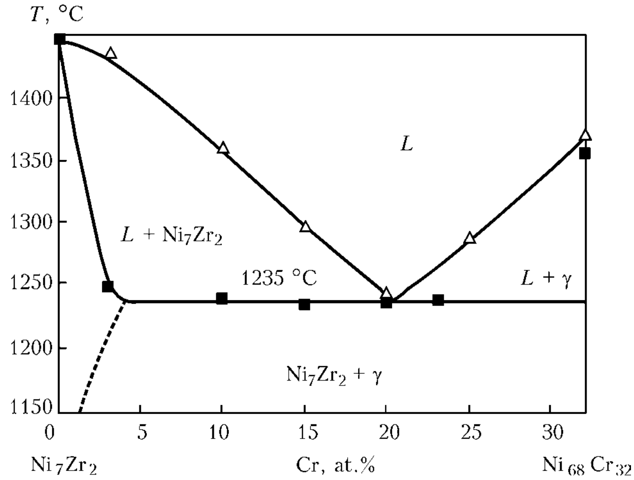

Figure 2. Quasi-binary section Ni_7Zr_2–$Ni_{68}Cr_{32}$: Δ, ■ — liquidus and solidus temperatures, respectively

(e.g. alloy 533) with a much lower content of particularly aluminium and titanium, and, hence, the γ′-phase. This alloy has heat resistance that is markedly lower than that of the base metal.

The brazing filler metals under consideration are eutectic alloys. Therefore, when they are used as filler metals for arc brazing, the seam metal contains a substantial volume fraction of eutectic (Figure 4). Naturally, in this case it is impossible to provide high values of heat resistance. And it is unrealistic to radically change structure of the seam by diffusion annealing within the time acceptable for practice, which is attributed to an insignificant degree of solubility of zirconium in nickel.

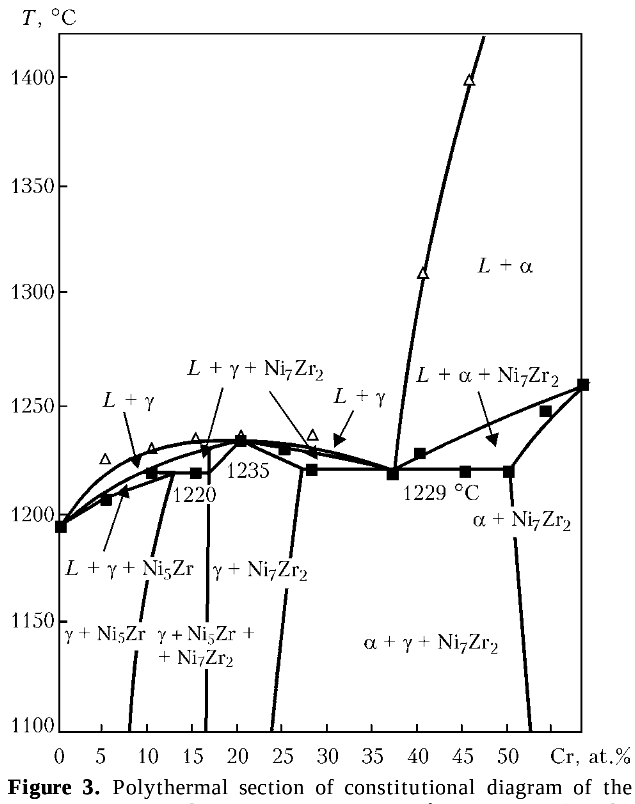

Figure 3. Polythermal section of constitutional diagram of the Ni–Cr–Zr system along an isoconcentrate of 8.8 at.% Zr (see designations in Figure 2)

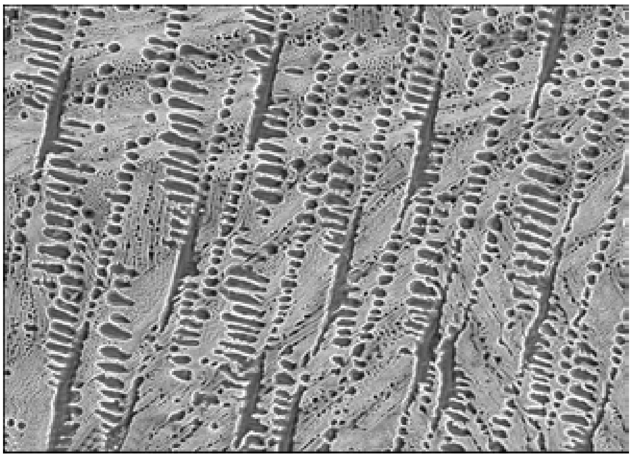

Figure 4. Microstructure of seam metal produced by arc brazing using filler metal of the Ni--Cr--Zr system (×550)

This drawback can be reasonably avoided through using composite filler metals, which are a mechanical mixture of powders of low- (eutectic alloy) and high-melting point (heat-resistant alloy) components. Amount of the high-melting point component can be varied within wide ranges (from 20 to 70 %). The target in development of a composite filler metal is to preserve a low wetting temperature of the base metal and radically change the composition of metal of the brazed joint by bringing it close to that of the base metal, i.e. it is necessary to try and ensure the maximum possible content of the high-melting point component in filler metal. Naturally, in this case a heat-resistant alloy can be provided in the seam after melting down the filler metal under the effect of arc heating.

Structure of metal in the zone of a joint produced by arc brazing using alloys of the above system as filler metals, depending upon the heat input and type of a filler metal (cast or composite alloy), was investigated in study [6]. As established, the use of the optimal heat input and composite alloy provides formation of the crack-free seam metal with a finely dispersed structure (Figure 5, *a*).

Consider in more detail structure and chemical heterogeneity of the deposited metal (Figure 5, *b*). X-ray microanalysis shows that the seam metal consists of an alloy that can be classed, according to its composition, with heat-resistant ones (Table 1). Of special notice here is a high mass fraction of aluminium (5.5 %) and titanium (2.9 %). Zirconium content 1.9 wt.%. Solid solution of a variable concentration (dendrites and metal in the dendrite spacing) with a high (about 0.2 wt.%) content of zirconium dominates in the seam metal. Fine carbide precipitates are located along the grain boundaries.

Annealing at a temperature of 1125 °C for 4 h resulted in a radical change in structure of the seam metal (Figure 5, *c)* and only a slight change in chemical composition.

It was difficult to clearly define boundary of the joint produced by arc brazing using a composite filler metal with a high content of the high-melting point component, as the deposited and base metals had almost the same etchability. After heat treatment (at

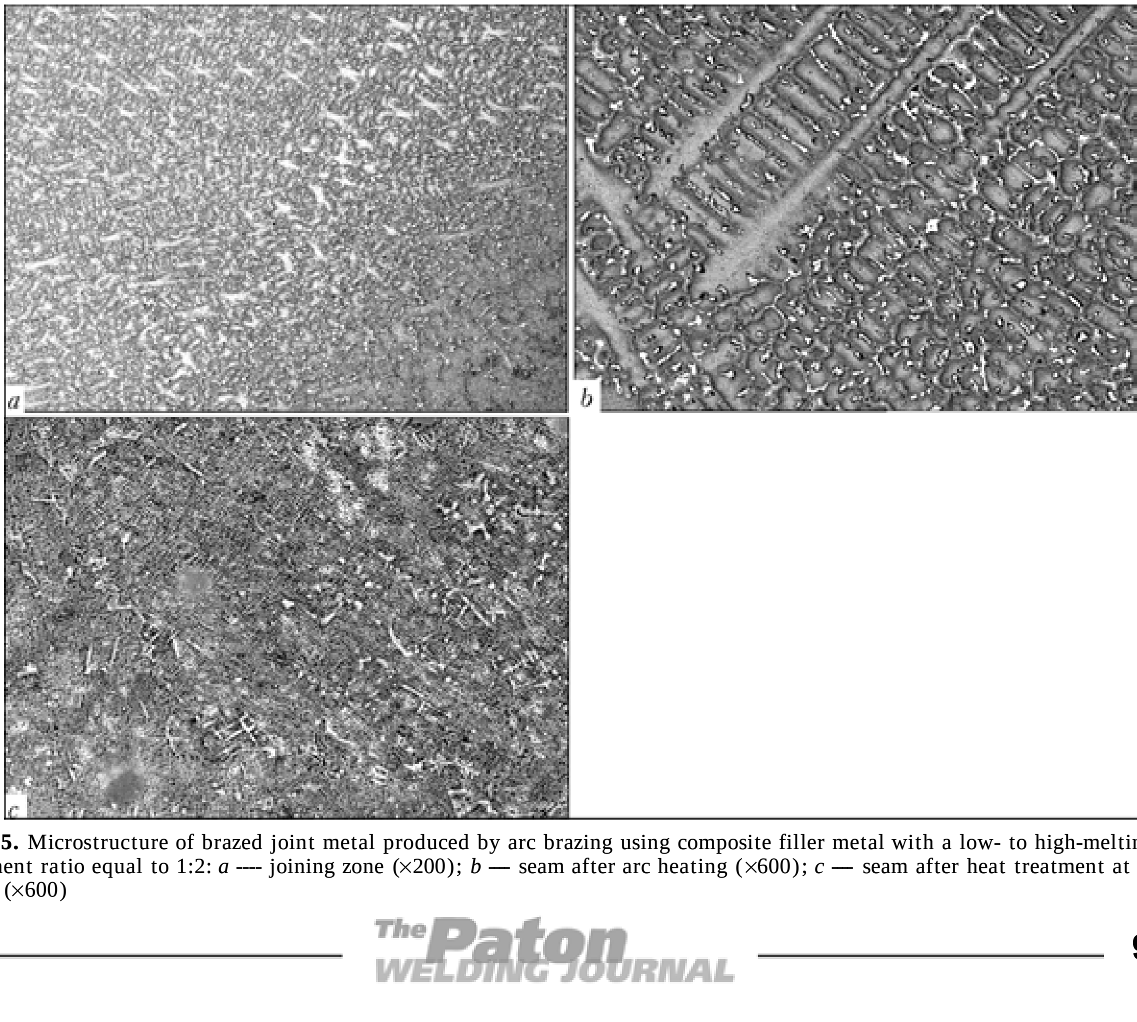

Figure 5. Microstructure of brazed joint metal produced by arc brazing using composite filler metal with a low- to high-melting point component ratio equal to 1:2: *a* ---- joining zone (×200); *b* — seam after arc heating (×600); *c* — seam after heat treatment at 1125 °C for 4 h (×600)

Table 1. Chemical microheterogeneity of deposited metal of the seams produced by arc heating and composite filler metal

Low- to high-melting point component ratio	*Region studied*	*Content of elements, wt.%**							
		Co	*Zr*	*Cr*	*Ti*	*Al*	*W*	*Mo*	*Nb*
1:2	Total metal surface	8.4	1.9	4.8	2.9	5.5	8.2	1.5	1.0
	Dendrite	9.9	0.2	5.9	2.3	4.9	9.6	0.8	1.0
	Metal in dendrite spacing	7.8	0.2	4.3	4.0	5.9	7.0	0.2	1.4
1:3	Total metal surface	7.9	0.7	3.6	3.1	6.0	9.2	0.8	1.3

*Nickel — base.

1125 °C for 4 h), a sufficiently uniform metal structure was formed in isolated regions of the seam. Most likely this is the eutectic of the γ–γ' phase within the grains that are sometimes bordered with the second phase (Figure 6).

Naturally, the composition of the seam metal structure can be radically changed through heat treatment, which results in formation of the finely dispersed γ'-phase.

The mean content of zirconium in the deposited metal is approximately 0.7 wt.%, whereas after heat treatment zirconium is hardly revealed. The high content of aluminium and titanium persists after both arc brazing and heat treatment.

Therefore, as experimentally found, a heat-resistant alloy with a high content of aluminium and titanium can be provided in the seam as a result of using a composite filler metal and arc heating, which means that the heat treatment can result in formation of a high volume fraction of the γ'-phase. Chemistry of the composite filler can be readily changed depending upon the chemistry of the metal brazed.

Consider now results of investigation of the brazing ability of intermetallic alloy γ-TiAl. Proceeding from heat resistance characteristics (up to 700–750 °C), this alloy can compete with high nickel alloys, being markedly superior to them in density (3.5 g / cm^3, compared with 8.9 g / cm^3, which is characteristic of nickel). This will make it possible to reduce weight of a gas turbine engine by 30 %. Alloy γ-TiAl has high strength at room temperature (650–700 MPa) and at 700 °C (320–350 MPa). However, its low ductility (at a level of 0.2–0.5 %) at room temperature, caused by ordered structure of γ-TiAl, limits to some extent the application of intermetallic alloys and makes their processing more difficult. Nevertheless, they can be used in many assemblies of the hot section of gas turbine engines, provided that methods for joining them and appropriate filler metals are developed.

Production of brazed joints in alloy γ-TiAl and selection of compositions of brazing filler metals involve problems associated with the fact that the range of variations in a content of alloying elements, at which no deterioration of mechanical properties or performance of base metal occurs, is very narrow. Besides, the rate of diffusion of many components of filler metals may substantially decrease because of formation of intermetallic phases with aluminium. For example, intermetallic inclusions are formed in the seam metal in the case of joints in intermetallic alloy XD (vol.%: Ti–45Al–2Nb–2Mn–0.8TiB$_2$) produced by diffusion brazing at a temperature of 1000–1100 °C using filler metals of the Ti–Cu–Ni and Cu–Ni / Ti / Cu–Ni systems [7]. These inclusions can be removed by subsequent heat treatment (at 1310 °C for 30 min). However, the heat treatment performed under such conditions may lead to a substantial growth of grain of the alloy. Three-layer filler metal Al–Ti–Al holds promise in this respect. Desirable structure of the seam metal can be provided by selecting a proper thickness of the titanium and aluminium foils. As stated in study [7], the silver, aluminium or Cu–Ni alloy foils are inapplicable for brazing intermetallic alloy γ-TiAl.

Copper foil 5 and 50 μm thick can also be employed as a brazing filler metal [8]. Advantages of copper used as a filler metal include an acceptable melting point and absence of especially undesirable intermetallics Ni_2AlTi, which are formed in the presence of nickel. The best results were obtained with the foil 5 μm thick and brazing under the following conditions: holding at 1150 °C for 10 min and subsequent heat treatment (1350 °C, 1 h). Strength (shear) of the brazed joints at a temperature of 20 °C (with intact fillet regions) is 250 MPa. After removal of

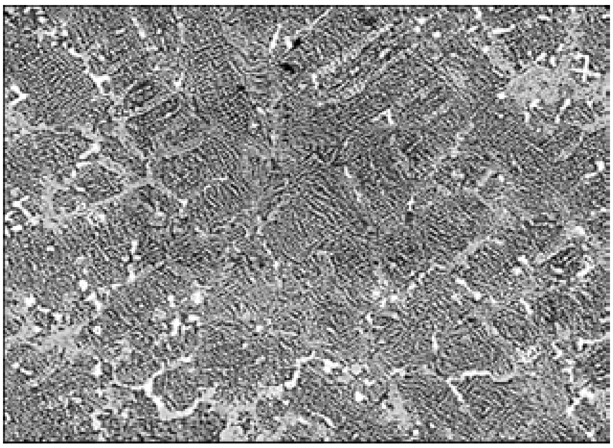

Figure 6. Microstructure of seam metal produced by arc brazing using composite filler metal with a high content of the high-melting point component after heat treatment (×600)

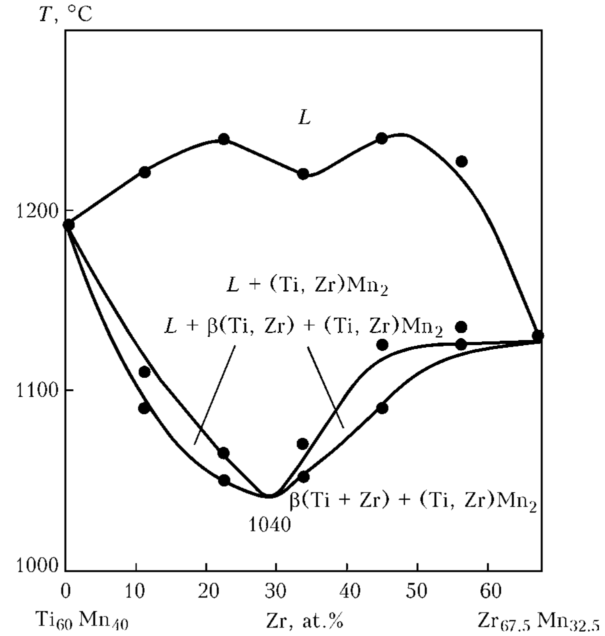

Figure 7. Metastable phase composition of alloys in section $Ti_{60}Mn_{40}$–$Zr_{67.5}Mn_{32.5}$ produced at a cooling rate of more than 0.5 K / s

the fillet regions and extra polishing of the samples this value of shear strength rises to the level of that of the base metal and equals 350 MPa. It should be noted that the base metal has a low strength value, which is probably associated with the effect of high-temperature heat treatment.

Alloys of the Ti–Zr–Mn and Ti–Zr–Fe systems are promising for development of brazing filler metals, as the Ti–Mn, Ti–Fe, Zr–Mn and Zr–Fe binary systems are characterised by the presence of relatively low-melting point eutectics, with melting points of 1180, 1085, 1135 and 928 °C, respectively, which are located between solid solutions β(Ti) and β(Zr), on the one end, and Ti- and Zr-rich intermetallics, on the other end [9]. Based on the isostructural character of compounds $TiMn_2$ and $ZrMn_2$, presence of continuous series of solid solutions in the Ti–Zr system, as well as the fusibility curves comprising temperature minimum, the region of compositions with a lower

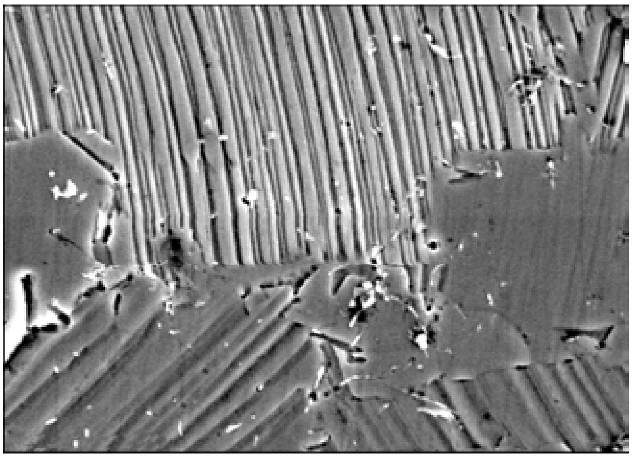

Figure 8. Microstructure of brazed joint metal in alloy γ-TiAl produced by using an experimental brazing filler metal of the Ti–Zr–Mn system (×1500)

solidus temperature than temperature of the eutectics in the limiting binary systems is likely to be formed in ternary alloys of the Ti–Zr–Mn system. Results of the fundamental research conducted at the E.O. Paton Electric Welding Institute and G.V. Kurdyumov Institute of Metal Physics proved existence of binary region β(Ti, Zr) + (Ti, Zr)Mn_2 in the Ti–Zr–Mn system. Figure 7 shows the polythermal section passing through the points of composition of binary eutectics in the limiting systems, reflecting the character of variations in solidus temperature of ternary alloys.

In the Ti–Zr–Fe system, variations in the temperature at which the eutectic in alloys within section $Ti_{70.5}Fe_{29.5}$–$Zr_{76}Fe_{24}$ starts melting are not that simple as in the Ti–Zr–Mn system. This is associated with a complex character of phase equilibria, leading to a change in nature of the intermetallic component of the eutectic.

Compositions of alloys of the Ti–Zr–Fe and Ti–Zr–Mn systems that hold promise for use as brazing filler metals were selected on the basis of the research conducted. Their morphological peculiarities were studied, and vacuum brazing of intermetallic alloy γ-TiAl of the 47XD grade produced by the powder metallurgy method was performed. To compare, the studies were conducted also on commercial brazing filler metals VPr-16 (wt.%: Ti–24Cu–13Zr–9Ni) and VPr-28 (wt.%: Ti–23Zr–16Cu–15Ni) [10], as well as experimental alloys of the Ti–Zr–Fe and Ti–Zr–Mn systems.

The JEOL scanning electron microscope equipped with a system of microanalysers was employed to study microstructure of metal of the brazed seams.

Mechanical tests of butt brazed samples of alloy γ-TiAl to short-time strength at 20 and 700 °C were carried out using the FP 100 / 1 testing machine. The long-time strength tests (according to GOST 3248–60 and GOST 10145–81) were performed using the AIMA 5-2 testing machine at constant temperature and load.

As shown by metallography of brazed joints in alloy γ-TiAl, the use of the commercial filler metals (VPr-16 and VPr-28) leads to formation of defects in the seams, such as lacks of penetration and cracks. Metal in the central region of a brazed seam (about 200 mm wide) is characterised by a clearly defined chemical heterogeneity: the eutectic component solidifies to form a continuous chain.

Table 2. Properties of brazed joints in intermetallic alloy γ-TiAl

Filler metal No.	*Alloy system and grade*	*Strength, MPa, at temperature, °C*		*Time to fracture of specimens at 700 °C, h, under load, MPa*	
		20	*700*	*140*	*200*
1	Ti–Zr–Fe	651	284	483	499
2	Ti–Zr–Mn	693	316	500	300
3	VPr-16	574	300	–	–
4	VPr-28	468	–	–	–

In brazing using the experimental filler metals, the eutectic regions formed in the seam metal are fewer, there are regions where the seam metal has a lamellar structure, close to that of the base metal (Figure 8). It should be noted that not only the compositions of filler metals, but also the brazing conditions are important for obtaining good results.

The strength test results (Table 2) show that brazed joints in alloy γ-TiAl, produced by using experimental filler metals Nos. 1 and 2, have a maximum short-time strength at room and increased temperatures, close to that of the base metal. In the long-time strength tests, the brazed joint samples did not fracture both under preset (140 MPa) and increased (200 MPa) loads (Table 2).

Therefore, brazing of alloy γ-TiAl using the developed filler metals provided joints close in structure and properties to the base metal. As of now, these filler metal can be used for brazing advanced different-application structures. Still, the topical problem is development of the technology for production of the required forms of new brazing filler metals, such as, for example, the rapidly quenched foils, extruded rod, etc.

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INVESTIGATION OF RESIDUAL STRESSES IN WELDED JOINTS OF RAILS PRODUCED BY FLASH-BUTT WELDING

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Calculation-experimental method of determination of residual stresses in the zone of welded joints was used. The basic data were obtained by mathematical modeling of the process of formation of elastic-plastic deformations during cooling of the welded parts up to the plastic condition.

Keywords: *flash-butt welding, pulsed flashing, welded joint, residual stresses, microstructure, mathematical model*

Welding is widely applied in construction of the continuous railway track for high-speed trunk-railways. It has to meet new goals now, as the length of welded sections increases from 400--800 m up to the length of an all-welded section, reaching several kilometers [1]. Use of sections of such a length increases the probability of generation of additional longitudinal forces in them, which is caused by external force impacts, for instance, mobile loading at variation of the conditions of train motion. This, in its turn, makes more stringent requirements of service durability of butt welded joints.

High-strength rails, in particular of electric steel, having a higher content of manganese, vanadium and nitrogen are widely used in continuous tracks (Table 1). Compared to rails produced in the previous years, they have a higher wear resistance and strength (Table 2). During fabrication the rails most often are subjected to bulk quenching, and then the HAZ sections are softened in welding. In this connection, additional heat treatment is required which in many cases is difficult to perform, and, moreover, it does not ensure restoration of the required properties of the metal.

Development of methods to lower the heat input in welding in order to reduce the extent of sections, which were exposed to high-temperature heating, is a promising direction in improvement of the technology of welding rails of high-strength steels. However, in this case it is necessary to take into account the fact that the considered rail steels are highly sensitive to quenching and application of highly-concentrated heating may lead to formation of critical hardening structures in the HAZ metal and development of considerable residual stresses in the weld.

Service durability of welded butt joints depends on the level of residual stresses. Under the conditions of cyclic loading, residual stresses change the values of average stress of the external loading cycle, which may promote initiation of a fatigue crack, or, contrarily, prevention of its initiation. Considering that most of the damage of butt welded joints on the track is of a fatigue nature, investigations of the residual stress state of welded rails are of not only theoretical, but also of practical interest [3].

Flash-butt welding is the process the most widely used in the world for rail welding. Over the recent years a new technology has been developed at the E.O. Paton Electric Welding Institute — pulsed flashing, which will greatly expand the technological capabilities of this welding process due to reduction of the welding allowance and providing the possibility of producing thermal fields with different temperature gradients in welding. This allows welding rails of different type, both surface-hardened and bulk-hardened [4].

Earlier research established that in welding such rails the heat input should be limited to avoid softening in the welding zone. However, application of welding modes with a high gradient of the temperature field increases the probability of defect initiation in the joint plane. In addition, with the use of highly-concentrated heating, increase of the residual stress level in the welded joints and lowering of their fatigue strength is anticipated, respectively.

Table 1. Composition of rail steel, wt.% [2]

Steel grade	*C*	*Mn*	*Si*	*P*	*S*	*Al*	*V*	*N*
M76	0.76	0.99	0.30	0.011	0.0175	0.013	–	--
E76	0.82	1.11	0.49	0.010	0.0060	0.011	0.11	0.014

Table 2. Mechanical properties of rail steel [2]

Steel grade	*Ultimate strength* σ_t, *MPa*	*Yield point* σ_y, *MPa*	*Relative elongation* δ, *%*	*Reduction in area* ψ, *%*	*Impact toughness KCU*, MJ/m^2
M76	1281	965	10	32.5	0.42
E76	1350	1010	13	44.0	0.44

The purpose of this work is evaluation of the influence of various thermal modes in flash-butt welding on the residual stresses and possible structural changes in the HAZ of welded joints on rail steel M76.

The work was performed using a calculation-experimental method to determine the residual stresses in the welded butt zone, in which the main data are obtained by mathematical simulation of the process of formation of elasto-plastic deformations with cooling of welded joints right down to room temperature.

Calculation was based on experimental data on temperature distribution in welded joint HAZ in flash-butt welding. The curves of temperature distribution in Figure 1 correspond to different variants of the modes of rail welding by continuous and pulsed flashing, at which sound formation of the joints is ensured.

Sound joints were obtained with all the given welding modes. In this case the width of the zone of structural transformations (temperature above 700 °C) in the welded joints produced in the «soft» welding mode (Table 3, variant 2) is 2 times greater than in «stringent» modes (variants 4 and 5). The structure of the HAZ metal and the strength properties differed, respectively.

Calculation was performed for three variants (2, 4 and 5) of the modes with different temperature fields (curves *2, 4, 5* in Figure 1, respectively), which were taken for the initial temperature distribution. Verified tools of the heat conductivity theory were used to follow the cooling process. The above idea has already been used more than once in several studies [5, etc.]. It allows significantly simplifying the solution of the thermal conductivity equation by eliminating from the calculation the process of parts heating in flash-butt welding.

Temperature calculation was performed using the algorithm of numerical solution of a 3D equation of heat conductivity at the initial and boundary conditions corresponding to the conditions of sample cooling. Calculation was performed using a computer program 3D developed at the E.O. Paton Electric Welding Institute.

Table 3. Results of static bend testing

Steel grade	*Variant of welding mode*	*Breaking load, kN*	*Deflection, mm*
M76	2	1900–2200 / 2100	38–55 / 45
	4	2000–2300 / 2130	43–60 / 53
	5	2250–2350 / 2300	41–63 / 46
E76	2	1800–2300 / 2040	17–30 / 20
	4	2120–2500 / 2180	31–45 / 35
	5	2050–2500 / 2350	28–36 / 32

Notes. 1. Variant 2 — continuous flashing; variants 4 and 5 — pulsed flashing. 2. Numerator gives minimum and maximum values, denominator gives average values.

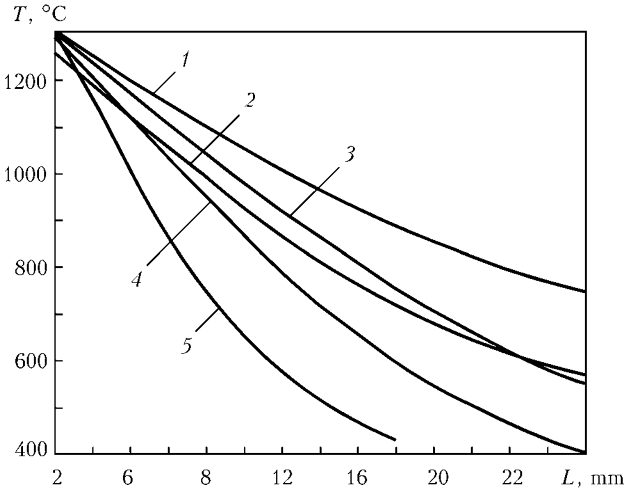

Figure 1. Temperature distribution in the welded joint HAZ before upsetting in welding in different modes: *1* — preheating (t_w = = 200–250 s); *2* — continuous flashing with a programmed voltage drop (t_w = 180–220 s); *3–5* — pulsed flashing (t_w = 110–120, 70–80 and 30–40 s, respectively)

The stress state was calculated using an algorithm for numerical solution of the problem of a non-isothermal plastic flow with Mises criterion [6], and the kinetics of microstructural changes in the HAZ of welded joints on steel M76 was described using the characteristics of the diagram of anisotropic calculation of austenite for steel with 0.77 % C [7]. Results of calculation of the longitudinal and transverse residual stresses are shown in Figure 2.

Validity of the obtained data was evaluated by the results of experimental measurement of the longitudinal and transverse residual stresses in the butt joints of rails on steel R65, made in the mode corre-

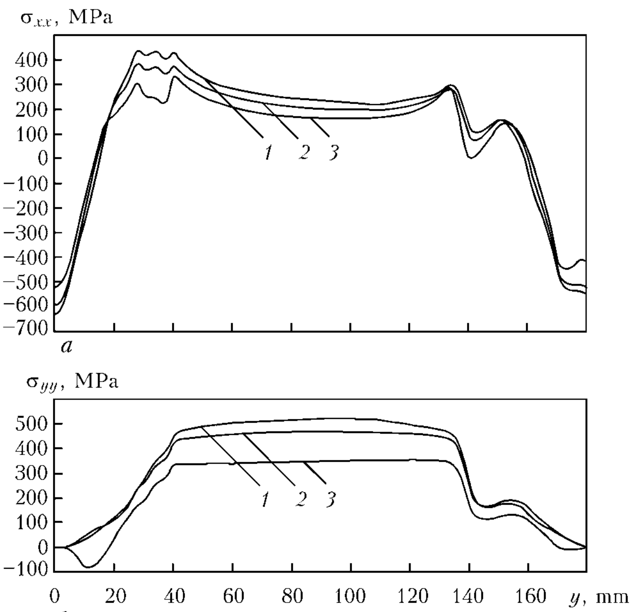

Figure 2. Calculated dependencies of longitudinal σ_{xx} (*a*) and transverse σ_{yy} (*b*) residual stresses, obtained for heating variants 2 (curve *1*), 4 (curve *2*) and 5 (curve *3*)

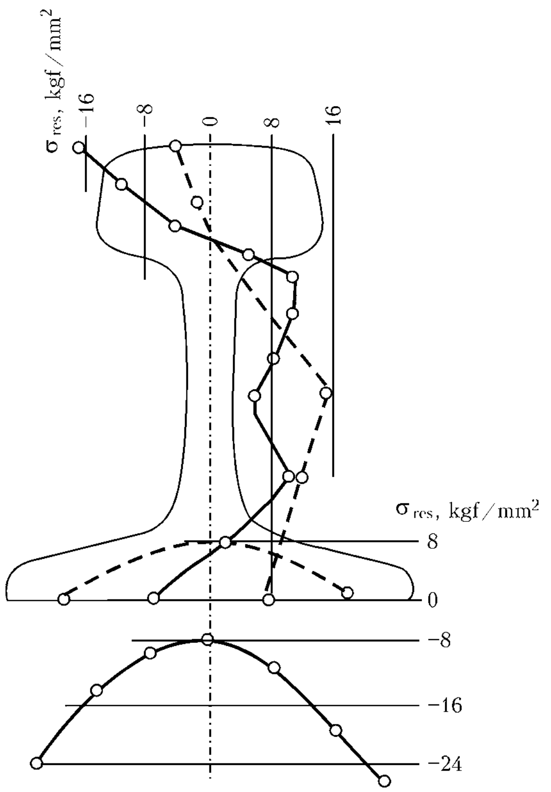

Figure 3. Results of measurements of longitudinal (*solid lines*) and transverse (*dashed lines*) residual stresses in the butt joint of rails of steel R65 (variant 2) [3]

sponding to variant 4 (Figure 2, curve *2*). Figure 3 shows the results of experimental measurement of the longitudinal and transverse stresses, which were taken by the method of cutting out templates by a procedure described in [8].

Comparing the obtained calculation data (see Figure 2) with the results of measurement of the residual stresses (Figure 3) leads to the conclusion that the accepted model yields valid results. The discrepancy between the calculation and measurement results is attributable to the fact that when experimental measurements are taken, stress values are averaged, because of a considerable length of the measurement base.

As is seen from comparison of the curves in Figure 2, change of heating of the rail butt joints in welding in a rather wide range practically does not affect the values of the residual stresses, or their distribution in the HAZ metal. It follows that application of highly concentrated heating should not have a negative influence on the mechanical properties of welded joints.

Heating influence on the HAZ metal structure is much more complicated. Increase of heating intensity results in narrowing of the HAZ and is accompanied by grain refinement in the metal structure in the near-contact area. When welding mode of variant 2 is used, the prevailing structure is pearlite, in the case of variant 4 it is sorbite, in the case of variant 5 it is sorbite with upper bainite (Figure 4).

In this case, grain refinement at testing for static bending leads to improved strength properties (breaking load becomes higher). At increase of heating intensity the ductile properties (deflection) first increase (variant 4, Table 3), and then decrease (variant 5).

Figure 5 gives calculation data on microstructural changes in the HAZ metal of welded joints on steel M76 at different parameters of the welding mode.

Many years of experience of operation of butt joints made using continuous flashing with a programmed voltage reduction (variant 2) demonstrated that the available level of residual stresses does not have any essential influence on their strength properties. In this case, the sites of martensite inclusions are either not detectable at all, or have a very small

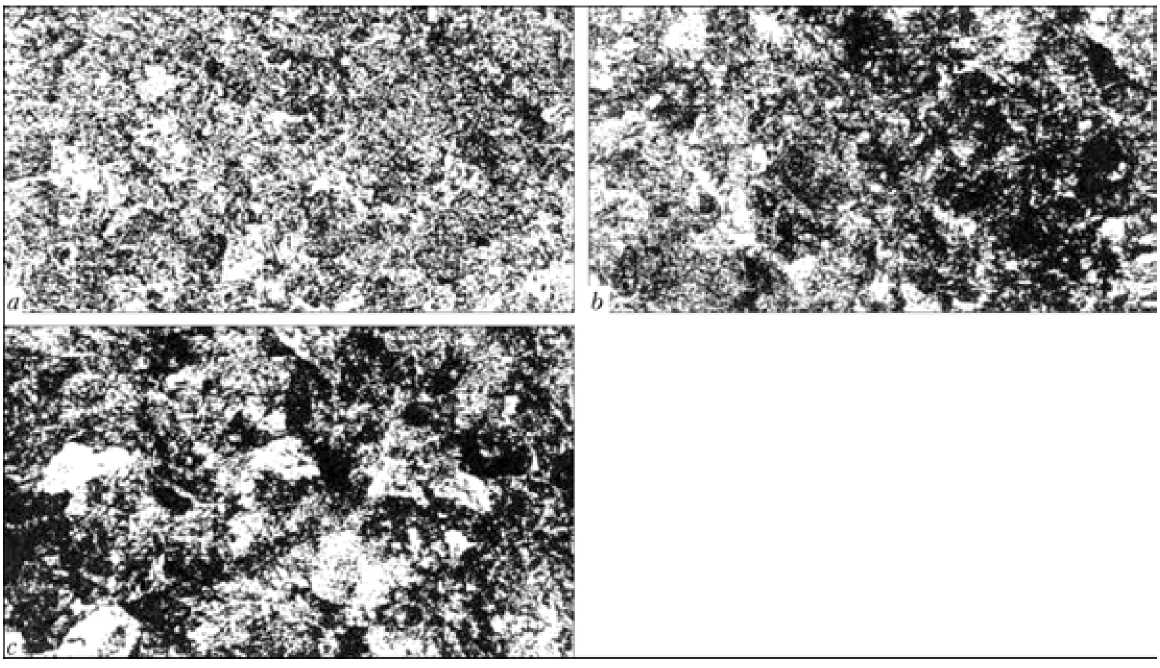

Figure 4. Microstructure of weld metal (3 mm from the joint line) at different welding time: *a*, *b* — pulsed flashing (t_w = 30–40 and 70–80 s, variants 4 and 5, respectively); *c* — continuous flashing with a programmed voltage drop (t_w = 180–220 s, variant 2) (×200)

length, and the load-carrying capacity of the butt joint does not depend on them.

As shown by investigations, no increase of the residual stresses is observed in welding in the modes of pulsed flashing close to variant 4 in terms of the heat input. Martensite structures formed in the HAZ metal do not lower the service endurance of the butt joints.

Application of more intensive modes of pulsed flashing, similar to variant 5, may promote lowering of the ductile properties of the welded joints because of a higher content of the martensite phase, which is eliminated by post-weld heat treatment.

CONCLUSIONS

1. The developed mathematical model allows obtaining valid results in calculation of residual stresses in welded joints, made by flash-butt welding.

2. Mathematical model of microstructural changes in the HAZ metal enables conducting comparative evaluation of welding modes on weld metal structure.

3. At heating variation in the temperature ranges, that may be ensured in continuous and pulsed flash-butt welding, distribution of inner stresses in the welding zone, or their magnitudes change only slightly. Therefore, application of «stringent» welding modes does not lead to an increased level of residual stresses.

4. At reduced heating the weight fraction of the main weld structure, i.e. bainite, does not change, and martensite weight fraction increases. Therefore, at selection of the welding modes it is necessary to allow for the combined influence of these two factors on producing the highest indices of ductile properties of welded joints.

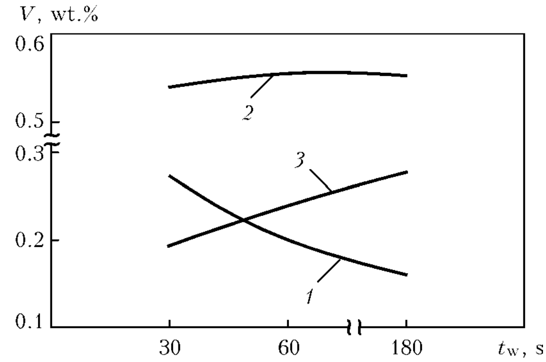

Figure 5. Change of weight fraction V of martensite (*1*), bainite (*2*) and ferrite-pearlite mixture (*3*) in microstructure of HAZ metal of steel M76 at different welding times

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SELECTION OF METHODS FOR COMPREHENSIVE ASSESSMENT OF WELDING EQUIPMENT QUALITY

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Models for determination of quality characteristics of welded equipment are considered. Assessment calculation of weighted average characteristics of quality of welding transformers, which are manufactured by a common technological scheme under the conditions of batch production, is given.

Keywords: *welding equipment, technical level, quality control, generalized quality factor, expert evaluation, matrix, vector, objective function*

The goal of improving the quality of welding equipment (WE) and its competitiveness is one of the major goals of manufacturer-companies. In this connection, the problem of development of the methods to evaluate the technical level of batch-produced WE becomes important. Unfortunately, this issue has not been given due attention over the last years. However, several works on mechanical engineering are known [1–3], the ideas of which can be adapted to evaluation of WE quality, allowing for the specific features of its manufacturing.

In order to solve the problem of quality assessment in quality control [4], various approaches have been developed, which are based on generalized quality criteria Q_g of WE, that may be considered in two aspects: first, comparison of Q_g with similar criteria, obtained for respective products of other companies, i.e. determination of WE technical level [5] among the analogs and prototypes; the second, determination of quality criteria by the results of measurement of the technical parameters of samples of batch-made products. Addressing the second problem is urgent for WE manufacturers, working to ISO 9001 requirements, which specifies continuous monitoring of the products being made.

Analysis of the methods of evaluation of generalized criterion of product quality. The first models of comprehensive quality assessment were constructed as a simple combination of assessments of individual properties of the item, without allowing from their importance [6]. This is the so-called comparison by the average value. It is natural that the effectiveness of such average assessments can only slightly satisfy the users. Introduction into the model [7] of weight factors, based on the mean arithmetic value, significantly increases their effectiveness and widens the range of the users. Analytically this assessment can be presented in the following form:

$$Q_g = \sum_{j=1}^{n} Q_j g_j, \tag{1}$$

where n is the total number of accountable parameters of the welding machine; Q_j is the quality criterion; g_i is the weight factor of j-th parameter.

Quality criteria based on the geometric-mean approach, are found by a simple multiplication of the differential factors, characterizing individual parameters. Usually, Q_g without allowing for the weight factors, is calculated by an equation from [8]:

$$Q_g = \sqrt[n]{\prod_{j=1}^{n} Q_j^{g_j}}. \tag{2}$$

If model (2) is made more precise by adding the weight factors, we have [9]:

$$Q_g = \sqrt[\Sigma g_j]{\prod_{j=1}^{n} Q_j^{g_j}}. \tag{3}$$

The model in the form of (3) did not become sufficiently widely accepted. Characteristic features of this approach are described in [9, 10].

Searching for new ways to substantiate the generalized quality assessment of industry products led some authors to development of models, based on the harmonic mean value of Q_g [6, 11]. Such an approach is necessary during analysis of differential parameters with large fluctuations, namely quality partial criteria (PC). This model is usually assigned in the form of the following expression:

$$Q_g = \left(\sum_{j=1}^{n} g_j\right) / \left[\sum_{j=1}^{n} (g_j / Q_j)\right]. \tag{4}$$

This assessment is an intermediate one between the arithmetic mean and geometric mean assessments and is rather seldom used for analyses of quality PC.

Selection of the model of Q_g evaluation for welding equipment. As is known [12], the discrepancy between quality assessments made by formulas (1)–(4) is quite large. Therefore, the reply to our question about which welding machine is better, will depend on the averaging method, as well as correct assignment of the weight factors. As WE technical characteristics (or its PC) vary in a narrow range (up to 20 %) in batch production, then we may use the weighted average values.

Thus, in order to solve the problem of determination of the technical level of samples of batch-produced WE, we need, first of all, the reference source, described by the vector of reference parameters $[P_{1(\mathrm{ref})}, ..., P_{n(\mathrm{ref})}]$, and, secondly, assigning of the regions characterizing the quality criteria. Replies to these questions can be found in GOST 233554.2--81 «Expert methods of evaluation of the quality of industry products».

There exist numerous approaches to expert polling. Work [13] shows that six models became the most widely accepted in quality control, which differ both in the problem definition and processing of the obtained data. One of the preferable methods of expert polling, which is recommended for WE, is the Delphi method [14], suggested by T.J. Gordon and O. Helmer. Its essence can be briefly described as follows:

- replies to the posed questions about PC should be given in the quantitative form;
- several questioning cycles are usually conducted, and the greater the data discrepancy, the larger the number of these cycles;
- after each questioning cycle all the experts are familiarized with the replies of the other participants;
- each expert must substantiate his opinion about the discussed WE characteristics with reference to published sources, codes, etc., this allowing various factors to be taken into account;
- statistical treatment of the obtained replies should be performed after each questioning cycle and all the participants should be familiarized with its results.

Thus, Delphi method essentially consists in revealing the tendencies of development of a certain type of WE. In this case direct discussions are eliminated, but after each questioning cycle the experts are able to evaluate their statements taking into account the opinions and arguments of other participants. Now, the questioning process can be considerably accelerated and its quality can be improved through Internet conferences, involving highly qualified experts.

Let us assume that we need to determine the weighted average quality factor (technical level) of a welding transformer. In keeping with the item certificate a set of PC are formed, which, depending on the objective function, either can be selected from the technical parameters, or can be their combinations (functionals). The formed set of PC should be as complete as possible, and should be determined by highly qualified experts in WE field. Actual set of PC is the basis, and can be regarded as the coordinates of the vector in the base space. If specific coordinate values are taken from the specification, then the obtained vector is the reference; now if the specific values of the coordinates are found by measurement of the item, then the obtained vector characterizes this item. A set of vectors form the matrix $[M]$, where the lines are the PC, and the number of columns is equal to item quality (including the reference).

The matrix $[V]$ of weight coefficients is then formed, which consists of the determined vectors. Any quantity of vectors can be used, but it should exactly correspond to the number of PC. Physical meaning of the weight factors consists in that each of them determines the relative contribution of its respective PC into formation of an average weighted quality factor, unambiguously related to the objective function. Weight factors are determined by Delphi method [12].

Further procedure consists in finding the product of matrix $[M]$ by the transposed matrix $[V]$ of the weight factors. Multiplication result is represented by a matrix, where the lines are formed of average weighted quality factors for a certain item (quality vector) based on objective functions, number of columns is equal to the number of objective functions, and the number of lines — to the number of items.

As an example, let us consider determination of average weighted quality factors of welding transformers in an array of one-type items, made by a common operational sequence. Let us regard as partial criteria a set of technical parameters, assigned by the specification. They include open-circuit voltage $U_{\mathrm{o.-c}}$ (V), short-circuit current $I_{\mathrm{s.-c}}$ (A), working current I_{w} (A), efficiency (%) and power factor cos φ (dimensionless).

The first line of the matrix $[M]$ consists of technical parameters, which are given in the specification (reference–vector). Next lines consist of specific values, produced by their measurement in the items during testing. As a result, matrix $[M]$ takes the form shown in Table 1.

Matrix $[V]$ of weight factors for two objective functions (welding-technological properties F_1 and power effectiveness F_2) consists of elements given in Table 2.

In order to prevent the influence of dimensionality of values included into matrix $[M]$, the latter can be modified by dividing each element of the respective column by its certificate value, i.e. by the first line element. The renormalization procedure is not mandatory, however, its absence in a number of cases

Table 1. Partial criteria produced by measurement of welding transformer characteristics

Sample (item)	$U_{\mathrm{o.-c}}$, V	$I_{\mathrm{s.-c}}$, A	I_{w}, A	*Efficiency, %*	*cos φ*
Reference	80	220	150	75	0.60
No.1	75	215	145	70	0.55
No.2	78	200	155	65	0.50
No.3	70	190	140	55	0.40

Table 2. Weight factors for objective function

Objective function	$U_{\mathrm{o.-c}}$, V	$I_{\mathrm{s.-c}}$, A	I_{w}, A	*Efficiency, %*	*cos φ*
F_1	0.9	0.5	1.0	0.7	0.5
F_2	0.7	0.5	0.9	1.0	1.0

Table 3. Relative partial criteria of welding transformers

Sample (item)	$U_{o.-c}$, *V*	$I_{s.-c}$, *À*	I_w, *À*	*Efficiency, %*	*cos φ*
Reference	1.00	1.00	1.00	1.00	1.00
No.1	0.94	0.98	0.97	0.93	0.92
No.2	0.98	0.91	1.03	0.83	0.83
No.3	0.86	0.86	0.93	0.73	0.67

Table 4. Quality criteria of welding transformers

Sample (item)	F_1	F_2
Reference	1.00	1.00
No.1	0.95	0.95
No.2	0.94	0.92
No.3	0.83	0.80

makes interpretation of the calculation results more difficult. After renormalization matrix $[M]$ takes the form shown in Table 3.

Product of matrices

$$[M]\cdot[V] = \begin{vmatrix} 1 & 1 & 1 & 1 & 1 \\ 0.94 & 0.98 & 0.97 & 0.93 & 0.92 \\ 0.98 & 0.91 & 1.03 & 0.87 & 0.83 \\ 0.86 & 0.86 & 0.93 & 0.73 & 0.67 \end{vmatrix} \begin{vmatrix} 0.9 & 0.7 \\ 0.5 & 0.5 \\ 1.0 & 0.9 \\ 0.7 & 1.0 \\ 0.5 & 1.0 \end{vmatrix} =$$

$$= \begin{vmatrix} 3.60 & 4.10 \\ 3.42 & 3.88 \\ 3.39 & 3.78 \\ 2.98 & 3.27 \end{vmatrix}$$

consists of absolute average weighted evaluations of the items which have passed the testing. Transition to relative units (compared to the reference) (Table 4) enables comparison of the items (within the objective functions) and ranging them by quality directly under the production conditions.

PC and values of weight factors can be formulated in a similar fashion also for other WE types (rectifiers, semi-automatic machines, inverters, etc.).

The described model for establishing a generalized evaluation of welding transformer quality and the algorithms derived on its base, were used by the authors of this work to create software for a specialized testing facility [15], developed at the E.O. Paton Electric Welding Institute in cooperation with SELMA Company. Program modules made using an integrated LabView package may be applied by WE manufacturers for a continuous monitoring of its quality.

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WELDABILITY AND ADVANCED PROCESSES FOR MATERIALS WELDING

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Available methods for materials joining, allowing for an aggregate state of a material within the joining zone, are analysed. The need to revise the term «weldability» and develop a generalised quantitative criterion for evaluation of weldability is noted. Necessary premises for development of advanced welding processes, including the hybrid ones, are considered.

Keywords: *welding, permanent joints, fusion welding, pressure joining, vapour-gas state, weldability, generalised criterion, advanced joining processes*

More than 110 years have passed since the date of official registration of the electric arc used as a heat source for welding of metals. Since then the fusion welding process has been holding a firm place among other processes for joining metallic materials. High efficiency, low cost and versatility led to an extensive development and application of the arc welding process for joining first plain iron-base steels, then complex-alloyed steels and, eventually, alloys of different metals. The electric arc, which is still dominant among other sources of local heating, is employed for performing the absolute majority (probably more than 80 %) of welding operations. Joining of materials under the fusion welding conditions is provided through their melting, i.e. through the liquid phase.

The challenge during the last decades has been in development and implementation of also other method for joining of metals. The processes of joining metals in solid state received commercial application. All these processes involve joining of metals brought to a plastic state due to the appropriate degree of compression (e.g. forging) at normal or increased temperatures. They include cold welding (joining of aluminium, copper and low-carbon steel), diffusion bonding, friction welding, resistance welding, explosion welding, magnetic-pulse welding, roll welding of a billet to produce bi- and tri-metal plates and others. These processes make it possible to form a joint in metallic materials through using their second aggregate state, i.e. solid phase.

Studies on utilisation of the third aggregate state, i.e. gaseous state, were started approximately 40--50 years ago. In this case the material is transformed into a vaporous state and then condensed onto a substrate. This provides a physical contact and joining of the condensed material to the substrate. Any material (metal or non-metal) in any required combination can be evaporated and then used as a condensed material. This can be done owing to the fact that mixing of materials in the vaporous state occurs in proportions close to the stoichiometric ones. Such joining processes as physical (PVD) and chemical (CVD) vapour deposition, i.e. physical and chemical vapour condensation of materials on the substrate, respectively, received acceptance primarily for deposition of coatings. In the first case the use is made of the ability of a material to be deposited by condensation from the vaporous state in the form of pure metal or alloy on the substrate of other material that does not participate in formation of the vapour phase. In the second case it is the possibility of forming a new material through chemical interaction with the surface of the substrate of a reactive material in the gaseous state. An example is formation of a layer of titanium nitrides on the surface of a titanium substrate due to reaction with gaseous nitrogen. A combination of the PVD and CVD processes can also be realised. An important fact here is that along with condensation (or chemical reaction) it is possible to provide a high-quality joint in materials of a different nature.

Vacuum vapour-gas processes gained an extensive development and were implemented in a large number of technologies. Therefore, the methods for welding materials using all the three types of the aggregate state (solid, liquid and vapour-gas phases) within the joining zone (Figure 1) were realised in practice to a larger or lesser degree in the form of specific technologies.

It is very likely that the use can also be made of the fourth aggregate state (ionic) of the matter. This is the case where materials are in a state of high-charged particles, i.e. ions, which can be transferred to the mating surface, provided that the appropriate conditions are available.

Formation of a joint in materials in the above aggregate states is related to local or general heat effect exerted on them. This results in conditions that change structural and stress-strain state of a material.

Different materials react to such changes in the weld and adjoining zones in their own way, depending upon their thermal-physical properties, completeness of structural transformations induced by the heat energy input and a number of other factors characteristic of given welding conditions. The entire set of the above changes determines the ability of a material to form a permanent joint with a guaranteed level of

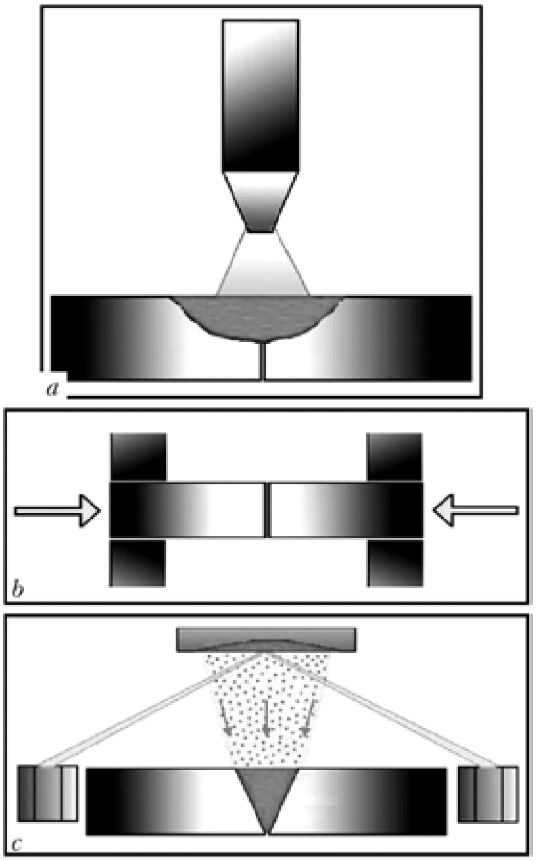

Figure 1. State of materials within the joining zone: *a* — liquid phase; *b* — solid phase; *c* — vapour-gas phase

performance. In the scientific literature this ability is termed «weldability».

Therefore, analysis or development of advanced processes for joining (welding) of materials should be premised on the following conditions:

- aggregate state of a material directly in the weld zone, in which the technology of joining (welding) of this material is realised;
- effect of the technology on structural and stress-strain state of a welded joint as a whole;
- relationship between the technology and generalised characteristic of weldability (joinability) of materials;
- economical, environmental and social peculiarities of a process.

The indispensable condition in this connection is the possibility of using the objective criteria of weldability (joinability) of structural materials.

On this basis, we will try and refine the term «weldability» of materials and consider some of the existing and advanced processes for joining structural materials.

Weldability. Much consideration has been given to weldability of materials during the entire period of existence of the welding science. There are dozens of national regulatory documents and international standards, wherein an attempt is made to define and specify the term «weldability» of materials. At the same time, recent publications merely confirm that the study of weldability is still one of the most important and high-priority issues of the world level. The term «welding» is gradually more and more replaced by the term «joining». In our opinion, these changes in terminology are of a conceptual character, implying a more general understanding of the process of making permanent joints in any materials, where the «weld» can be formed omitting the stage of melting of materials and have no clearly defined sizes and attributes.

Consideration of modern materials used to fabricate welded structures shows that many of them, proceeding from the existing concepts of weldability, are hard to weld or unweldable at all. Nevertheless, it is a reality now that permanent joints can be produced from such absolutely brittle materials as ceramics, glass, high-strength steels and alloys, cast irons, composites and single crystals. That is, the term «weldability» (joinability) of materials requires a new interpretation.

It is apparent that the terms «weldability» and «joinability» should allow for a set of data on a material to be joined (chemical composition and structural state); effect of an intended technology on the material welded (joined), structural and thermally stressed state, formation of defects and properties; and effect of environment on the material welded (joined) during its operation in a part (time variations in structure and properties caused by the presence of a welded joint in a part).

Almost in all known, both international and national, standards, the mention is made in the definitions of weldability that it is necessary to have «a corresponding technological process», «certain welding process and certain technology», «be welded by any method» and «using no special measures» (in the case of perfect weldability), «by an established technology» or «by a given method», i.e. it is noted that a technology as it is does have an effect, but the recommendations given are of a conditional or philosophical character.

In all the cases the definitions of weldability include, in this or that form, such notions as «own qualities of welded parts as well as structures they form», «the welds should comply with the corresponding requirements for properties and influence on a structure a part of which they are», «production of a joint with properties allowing a complete utilisation of the material», or «a welded joint should meet requirements stipulated by design and service conditions of a product», i.e. all these notions feature a subjective judgement of properties of the joints to be produced.

Many years of the world experience in using welding enable formulation of the following statements, which should be allowed for to refine the term «weldability»:

- weldability (joinability) is a property of material;

Weldability of different materials allowing for their aggregate state within the joining zone

Type of material	*Weldability in fusion welding*	*Weldability (joinability) allowing for aggregate state of material*		
		Liquid phase	*Solid phase*	*Vapour-gas phase*
High-strength aluminium alloys	Limited	Limited	Well-weldable	Good
High-strength titanium alloys	Same	Same	Same	Same
High-strength steels	Hard-to-weld	Hard-to-weld	Limited weldability	»
Nickel superalloys	Unweldable	Unweldable	Same	»
Intelligent alloys	Limited weldability	Limited	»	»
Granulated cast powder materials	Same	Same	»	»
Amorphous, microcrystalline materials	»	»	Not studied	»
Nano-structure materials	Unweldable	Unweldable	Limited weldability	Limited weldability
Polymeric composite materials	Same	Same	Same	Good
Intermetallics	»	»	»	Same
based on Al ($Al + B_2Al + SiC$)	»	»	Unweldable	»
based on Ti (Ti_3Al (α-phase), TiAl, Ti_3Al (γ-phase))	»	»	Good	»
based on Ni (Ni_3Al, NiAl, NiAl–Mo)	»	»	Hard	»
based on Ñî (Co_xAl_y)	»	»	Same	»
Ceramics	»	»	Unweldable	»
Adapted composite materials	»	»	Limited weldability	»
Carbon fibre reinforced plastics (AKM-1U)	»	»	Same	»
Metal-polymeric materials	Limited weldability	Limited weldability	»	»

• weldability (joinability) in a conventional sense varies depending upon the technology used for a given type of structures;

• a weldable material can become unweldable (Table) with a change in a technology, and vice versa;

• technological processes of joining are different for different aggregate states of the weld formation both in their physical principle and in heat (force) impact on a material welded (joined);

• for different technological processes the heat and force impacts on the weld and HAZ exert a different degree of influence on structural, physical-chemical, mechanical and other functional properties of materials;

• the heat and force impacts influence the value, character of occurrence and fixed magnitude of current and residual stresses and strains in a material welded (joined), as well as in a joint as a whole;

• a technological process and accompanying heat and force impacts on a material, as well as stress-strain state, determine the level of degradation of the material. The latter is estimated relative to the initial material or requirements for permissible values of functional properties and quality both during the process of fabrication of a structure and during its operation.

The above statements allow a new formulation to be put forward to define «weldability» (joinability) of materials. *Weldability (joinability) is the property of a material to form a permanent joint of the required quality and level of physical-mechanical and functional properties exhibited both during the process of its production and during operation of a product. Weldability is determined by the extent of degradation of properties of the joint as a whole and should be estimated as an integral indicator.*

Weldability can be controlled through varying the extent of degradation.

Improvement of methods for materials joining. Availability and utilisation of the three aggregate states of materials in formation of the weld and joint as a whole, as well as natural willingness to ensure in this case a minimum degradation of materials, serve as the basis for development of new processes or improvement of the existing ones. As noted above, the degradation implies not only an actual change in chemical and structural composition of material, but also a change in its thermally stressed state and properties both during the process of production of a joint (part) and during the process of its specified life time. The need to ensure a minimum permissible extent of the degradation in realisation of a joining technology imposes certain limitations or requirements on the process proper. In a general form, they can be reduced to the following: minimum possible heat input into the zone of formation of a joint; control of structural and chemical compositions and properties of material within the zone of a joint; maximum possible limitations of the weld and HAZ sizes; control of the stress-strain states in production of a joint; cost effectiveness and environmental safety of the process.

Consider some of the advanced joining processes from this standpoint.

Fusion welding (joining). For many years to come the classical fusion arc welding will remain dominant over the other welding processes (electron beam, laser etc.) in volume of application. At the same time, there is an increasing demand for new methods for joining (welding) of materials. This demand is stipulated by a number of factors, the most important of which are as follows:

- the electric arc as a concentrated heat source (heat input into the material welded) has lost its leading position, compared with electron beam, laser and now hybrid welding processes;
- melting of the base and filler metals by the arc and formation of the weld result in irreversible changes in a welded joint. This concerns residual stresses and strains, structural states of metal changing to the worse as a result of different thermal-physical and structure-sensitive properties of base metal. And only special arrangements, such as preweld or postweld heat treatment, can help to avoid this drawback in welding, for example, of high-strength steels;
- there are very many new structural materials now, which in general terms for a number of conditions are considered to be «unweldable» or have a «limited weldability» in arc welding. That is, the classical arc is incapable of producing functionally good welded joints. In other words, heating by the electric arc transfers these materials (composites, intermetallics, polymeric plates, amorphous glasses, microcrystalline materials with nano-structure, etc.) into the category of unweldable materials;
- requirement for introducing a large amount of filler metal to form the weld and, therefore, the need to perform operations associated with edge preparation, manufacture and application of welding wires, electrodes and fluxes make the welding fabrication much more expensive and complicated.

The new advanced processes of fusion welding deserving special consideration include (Figure 2) different combinations of hybrid processes (e.g. laser + plasma, laser + TIG, etc.), TIG welding using activating flux (A-TIG), micro arc welding using a micro wire filler with a diameter from 0.4 to 0.6 mm, microplasma powder welding and cladding using ultra dispersed powders, including of composite materials, and reactive-diffusion bonding.

These processes provide the possibility of decreasing the heat effect of the arc with a simultaneous

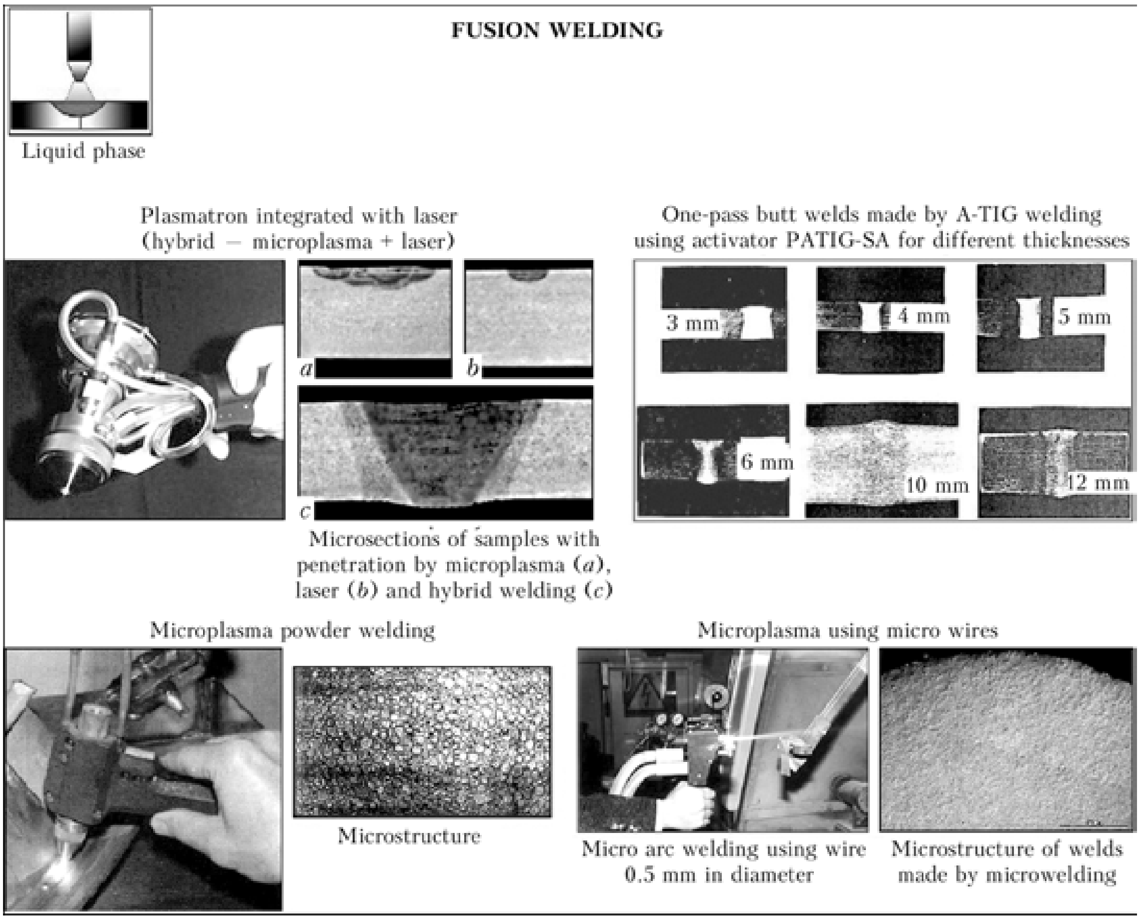

Figure 2

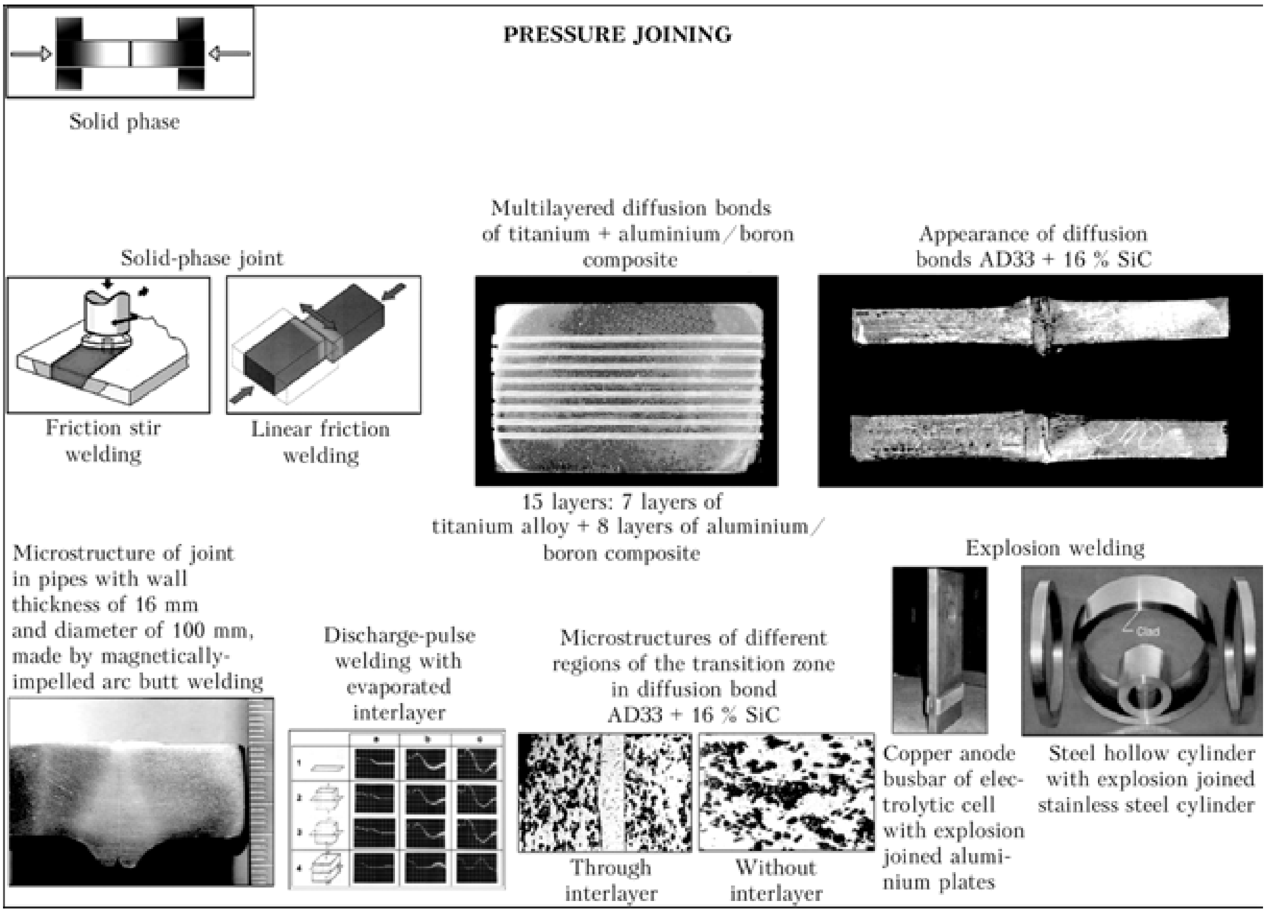

Figure 3

increase in the efficiency of melting and decrease in size of the weld and joint as a whole. It is very likely that activation and localisation of the process of melting of metal welded will remain one of the priority directions.

Worthy of special notice in this respect is the minimum-gap reactive-diffusion bonding process, which allows precision parts of complex configuration to be produced.

Solid-state joining. Flash butt and resistance welding processes have been successfully employed in industry for many years. Different types of capacitor-discharge welding, friction welding, diffusion bonding and explosion welding proved the possibility of joining hard-to-weld, including dissimilar, materials with a very high quality and a decreased extent of the degradation, compared with fusion welding.

A special breakthrough has been achieved in friction welding. It is apparent that joining in solid or quasi-solid state will be intensively developed in the future. One may expect that the new efficient ways will be found to activate the mating surfaces of the parts joined in solid state. This will enable the energy input necessary to form a joint to be decreased and, therefore, the subsequent degradation of material to be minimised.

The following processes are worthy of special notice among the new solid-state joining processes (Figure 3): various modifications of friction welding, diffusion bonding of materials using interlayers that activate the bonding process, discharge-pulse welding involving evaporation of the interlayer, and condensation and implantation of the consumable electrode material, magnetic-pulse and percussion welding in vacuum, magnetically impelled arc butt welding, and modifications of explosion welding.

Joining of materials in vapour-gas state. This type of joining has received acceptance primarily for deposition of coatings. The most promising process in this respect is electron beam evaporation (EB PVD). This process enables different compositions with different structures to be produced as monolithic materials (including within the joining zone).

Figure 4 shows flow diagram of the process of electron beam evaporation of materials, microstructures of composite materials based on metals and ceramics, as well as parts in the form of structural materials and thermal barrier coatings. Joints between dissimilar materials (metal + ceramics) are characterised by a high quality and low degradation of properties. This principle of producing composite materials, including for formation of joints (welds), holds high promise both as a process and as a system for alloying the welds.

CONCLUSIONS

1. Reliable joints in many structural materials can be produced owing to availability of different aggregate states of materials within the joining zone.

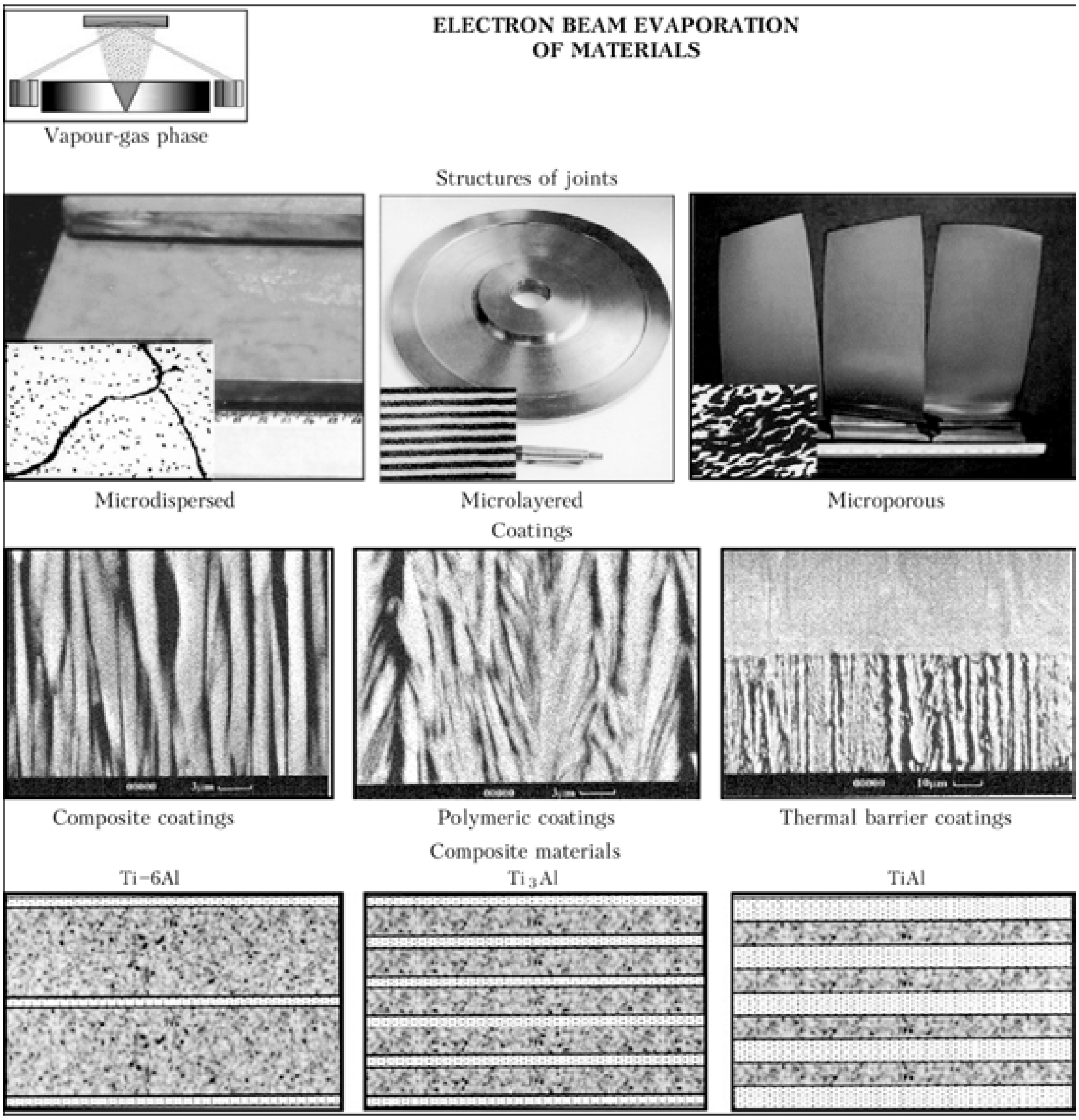

Figure 4

2. It is suggested that the joinability (weldability) should be considered to be the property of material, and that it should be estimated depending upon the technology used for joining on the basis of the extent of the degradation of material compared with this material in the initial state.

3. Control of the weldability (joinability) can be realised through varying the degradation of material.

STATE-OF-THE-ART AND PROSPECTS FOR DEVELOPMENT OF WELDING BY EXPLOSION AND HIGH-VELOCITY IMPACT (REVIEW)

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State-of-the-art of commercial technologies of welding by explosion (using explosives as the energy source) and high-velocity impact (using pneumatic and powder channel devices, as well as high-velocity water jets as energy sources) is analyzed. Separate consideration is given to attempts to develop a hand tool for local (spot) high-velocity impact welding. Possible trends in development and upgrading of the technologies of welding by explosion and high-velocity impact are considered.

Keywords: *explosion welding, high-velocity impact welding, structural materials, manual tools*

Explosion welding (EW) has been used with success in different industries for more than 40 years now. Review materials describing the experience of EW application have been published in special literature several times [1–4].

The main areas of EW application in ex-USSR and CIS countries are production of bimetals and making tubesheets of them for high-capacity heat-exchangers of up to several tons weight, two- and three-layer materials for equipment exposed to aggressive media, cladding of HEP turbine blades with cavitation-resistant coatings, applying bronze coatings onto slide surface of heavy-duty bearings. According to the data of [3], there exist more than 260 joints of dissimilar metals, produced by EW and having found practical application. Carbon and low-alloyed steels are mostly used as the main layer, and high-alloyed steels and copper, nickel, titanium, aluminium alloys, as well as zirconium and tantalum are used for the cladding layer. Long-term experience of service demonstrated the endurance and reliability of joints produced with EW.

The main areas of EW application are generalized and classified in Figure 1.

As the above information is generally known, let us further on dwell on the cases of EW application, which the author learned about over the last years through his personal initiative and development of cooperation with several foreign companies.

SMT Company (Shockwave Metalworking Technologies, the Netherlands), organized in 1962, has successfully mastered production of bimetals of different combinations and dimensions. The main areas of their application are shipbuilding (steel + aluminium transition pieces (Figure 2)), chemical and petroleum industry (cladding pipes and products from them with anticorrosion coatings, making tubesheets for heat-exchangers, pipe joining), car making (brake plates and bearings), electrical engineering (current-removing bimetal rails, transition pieces for high-current circuits), different products with anticorrosion and wear-resistant coatings. The Company has two pumped-down explosion chambers of 40 and 150 kg capacity in the trinitrotolyol equivalent and has extensive experience of EW in deep vacuum. Company specialists state that EW performance under vacuum allows reducing edge lacks-of-penetration and increasing the total area of the clad product by not less than 20 %, as well as lower the sound side effect of the explosion, which is of principal importance to meet the European noise criteria during performance of blasting operations.

Dynamit Nobel Company (DYNAPLAT trade mark, Germany) was one of the first to master industrial production of EW for corrosion-resistant bimetals for the chemical industry (tubesheets for heat-exchangers), non-ferrous metallurgy (transition pieces for high-current electric circuits), vacuum process equipment (tubular stainless steel + aluminium transition pieces), and shipbuilding. The Company has an open testing ground and underground area for conducting blasting operations, as well as equipment for straightening the explosion welded products and their testing. An important technical parameter of the Company potential in EW field is production of pipes clad from the inside by a tantalum coating (Figure 3). Pipe diameter is 1500 mm, length being 7500 mm, wall thickness being 15 mm, coating thickness being 1 mm. All the company products are certified to international standards.

Nobelclad Company, France, has been using EW since 1968 for bimetal manufacture, and it is one of the three world leaders in this field. Company products are highly diverse. EW is used in the manufacture of chemical and petrochemical, nuclear and thermal equipment (Figure 4), in hydroenergetics, manufacturing of pumps and paper, food industry, agricultural engineering, making high-current bimetal transition

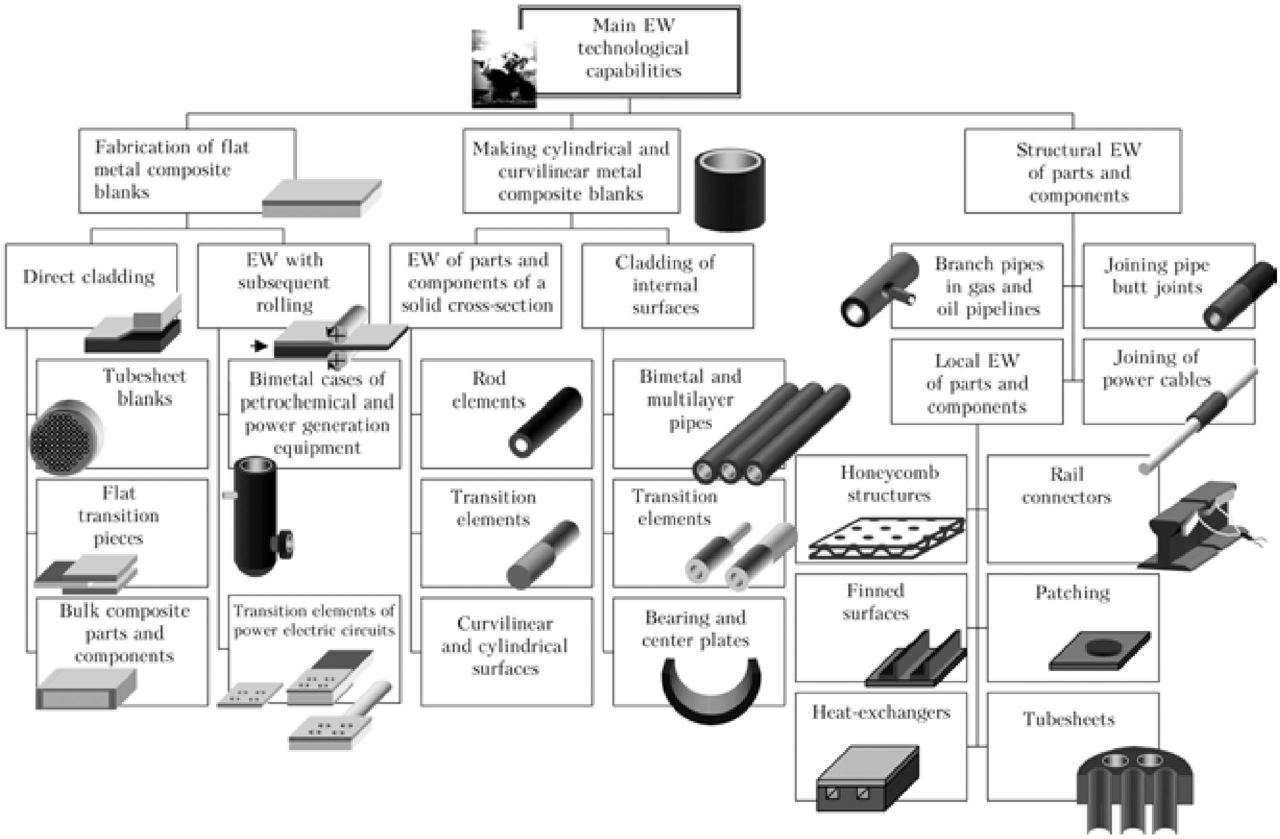

Figure 1. Main technological capabilities of explosion welding in keeping with the classification given in [4]

pieces and other products. One of the priority kinds of products are steel-aluminium items for shipbuilding.

The main parameters of explosion-clad products can be as follows: base metal thickness — 2–500 mm, cladding layer thickness 1–30 mm, maximum overall dimensions 11.6×4.5 m, area of one-time cladding — 34 m^2, maximum weight — 40 t.

There exists unique equipment for support of blasting operations and straightening the clad blanks, as well as fast destructive and non-destructive testing of their quality. All the company products are certified to international standards.

Nitro Metall AB Company, Sweden, which is a spin-off of the Nitro Nobel Group, makes a broad range of products, also for nuclear engineering, shipbuilding and oil production in the North Sea. Maximum thickness of bimetal plates is up to 300 mm, and their area is 30 m^2. The Company performs explosion cladding of bimetal and multilayer blanks and products for such applications as construction of sea icebreakers and liquid nitrogen transportation vessels (Figure 5). The latter use 4-layer (aluminium + titanium + nickel + stainless steel) transition pieces, which provide fastening of spherical storage tank for liquid nitrogen to the vessel hull. The Company has

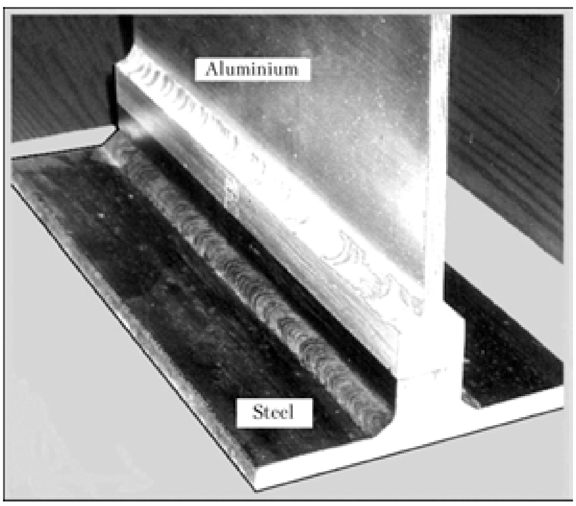

Figure 2. Joining aluminium to steel by arc welding through a bimetal transition piece made by EW

Figure 3. Pipe of 1500 mm diameter clad on the inside by a tantalum layer using EW

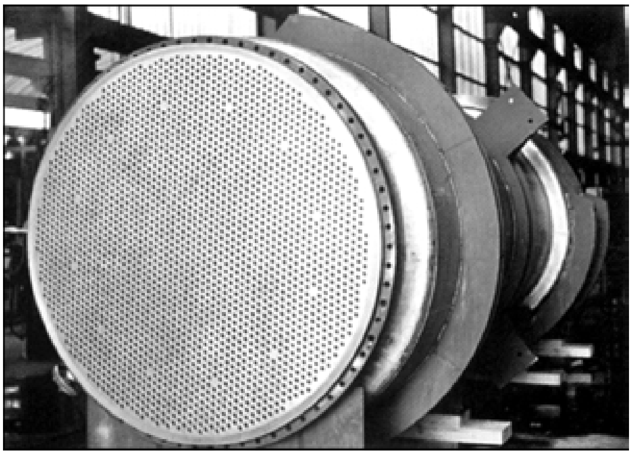

Figure 4. Heat exchangers made using a bimetal (steel + titanium) tubesheet

a research laboratory on product quality control to ISO 9002.

A number of other companies in Europe deal with EW, but it does not seem possible to describe their activity within the scope of this review (not is it necessary, as in terms of technical capabilities, quality and cost factors they are involved in competitive manufacture of similar products).

Over the last years EW technologies have become widely introduced into the industry of some countries in South-Eastern Asia, in particular Republic of Korea. Companies, which are the best known in this country, such as HAN-WHA (Korea Explosives), Korea Heavy Industry Inc., DAEHWA should be noted. These companies mostly use the technologies adopted from Western countries, but the level of their implementation is almost on a par with that in the West. Bimetal materials with coatings of stainless steel, titanium, nickel alloys, copper, bronze, Hastelloy in sheets of up to 30 m^2 area are made in Japan under BACLAD trade mark. It is obvious that EW is gradually becoming a process operation accessible for most of the industrialized countries of the world.

Local EW (spot or linear) is used in cladding large-sized sheets, when metal joining over the entire surface is not necessary. Application of these methods drastically reduces the explosive consumption, and lowers product cost. The simplest method of local EW envisages placing the explosive charge in the form of a strip on the flyer plate, which is followed by immersing the welded plates into a vessel with water at the depth of 5--50 cm. The water which is under the charge limits the free acceleration of detonation products and enlarges the zone of directed impact of the explosion. However, the effectiveness of this process is low and it is not readily adaptable to fabrication.

The E.O. Paton Electric Welding Institute developed a more efficient and readily adaptable to fabrication method of local EW. Its essence consists in that a cylindrical explosive charge with the detonation rate of 6000–8000 m / s and density of 1.60–1.65 g / cm^3 is placed into a shell of an inert material (rubber or plasticin). The charge is located on the

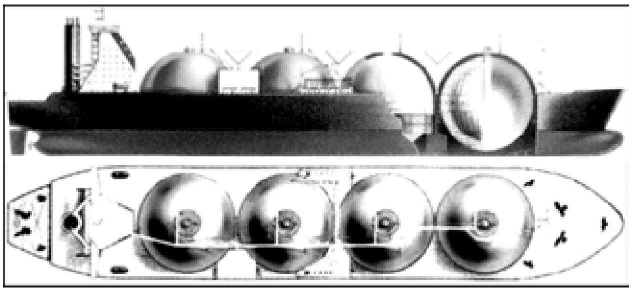

Figure 5. Schematic of a ship for transportation of liquid nitrogen using 4-layer transition pieces made with EW

surface of the plate to be welded, normal to it (for spot welding) or along it (for linear welding). Kinematics of the process of local EW is shown in Figure 6 in the from of fragments from «Welding and cutting by explosion» film (E.O. Paton Electric Welding Institute, 1979) and requires no explanation.

Local (spot) welding can be also conducted in the mode of high-velocity impact (HVI), not requiring the application of the explosive, which is indicated by the experience of world wars of XX century. This process is of indubitable interest for current practice primarily in terms of the possibility of a relatively simple implementation of this mode under the laboratory and shop conditions. In addition, the modes of HVI, unlike EW, are not accompanied by the action of residual pressure of the detonation products or excess pulse impact on the item.

Electromagnetic accelerators, powder and pneumatic channel systems, high-velocity water jets and other accelerators or strikers can be used as energy sources for acceleration of the flyer plates or parts to the required velocity of 250--500 m / s in the existing HVI methods. All of them should ensure in the collision zone the plastic deformation of the surfaces being welded to the specified depth and their strong adhesion.

A technology the most widely accepted ever since 1950s, which may be regarded as HVI, is that of magnetic-pulse welding, the principles of which and the respective equipment were developed at the E.O. Paton Electric Welding Institute [5]. Similar developments, made by Pulsar, Ltd., Israel, are widely accepted now. Acceleration of the parts being welded and their collision by this technology are performed at an angle (similar to EW) by a pulse of a strong magnetic field (Figure 7). The technology turned out to be highly convenient and effective in batch production of coaxial items, ensuring overlap joining of dissimilar materials, in particular, aluminium + copper. However, industrial application of this technology involves the need to develop or purchase expensive equipment.

Methods of HVI using channel systems are rather widely required, particularly in the recent years. As follows from published sources and advertisement materials, several variants of such systems have so far been developed. HVI, as a physical effect, was first reported by the researchers of the high-velocity impact in 1965 [6]. It was found that at hypersonic impact

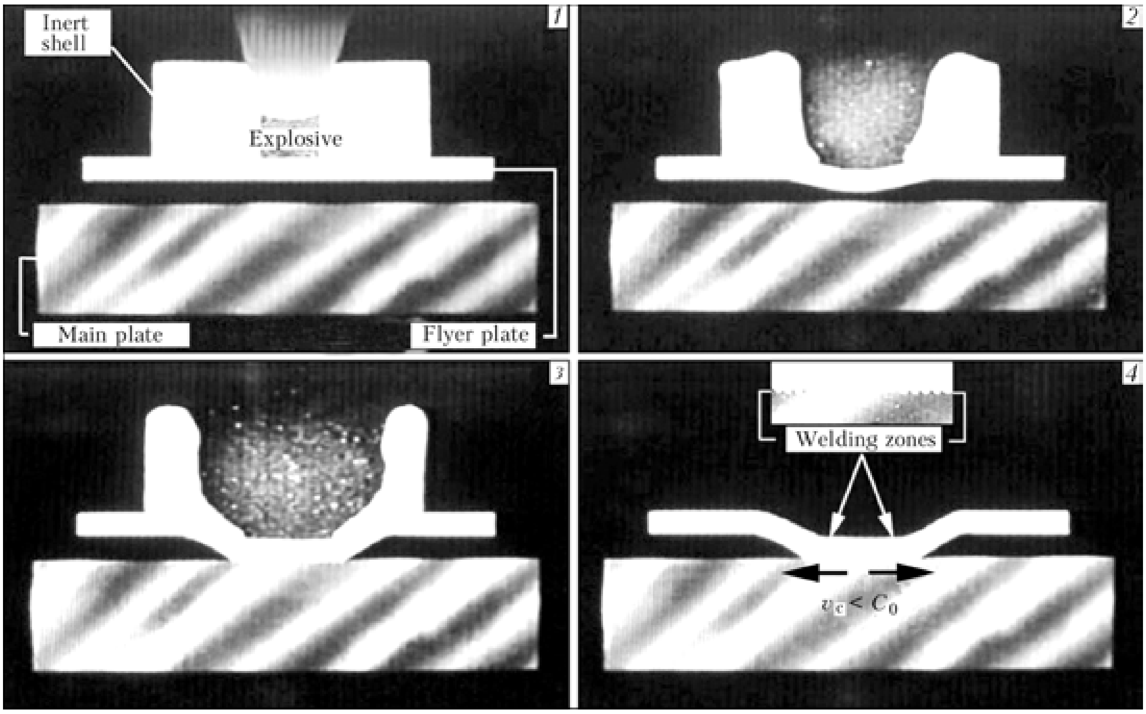

Figure 6. Kinematics of the process of spot (linear) welding by a cylindrical explosive charge, placed into an inert material shell: *1–4* — frames of the process sequence

of microparticles or strikers on the material, which is in contact with another material, a spot weld forms between the materials in the impact location.

Approximately ten years later Exploweld, Ltd. (Sweden-England-Scotland) presented in its promotion sheet a HVI method and a device for its implementation in the form of a portable hand gun for spot welding (Figure 8). High-velocity impact of the plate on the base results in formation of a joint around the circular surface. Device weight is 6.5 kg, and caliber is 18 mm. Thickness of the plate being welded on is not more than 3 mm, diameter of the welded spot being usually equal to approximately 15 mm. Depending on the thickness of the plate being welded, three sockets of different power are used. Combinations of the materials being welded are the same as in EW, but the welded plate should have high ductile properties as far as possible.

In 1990s the first papers were published about the then new process of HVI of metal studs [7, 8]. A

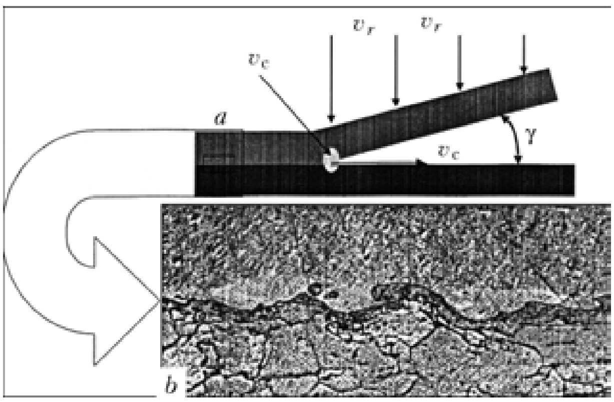

Figure 7. Block-diagram of the process of magnetic-pulse welding (*a*) and microstructure of the welded joint (*b*); v_c — velocity of the contact point; v_r — collision velocity

device for HVI was designed on the basis of a hand gun of 9.5 mm calibre (Figure 9). Sound joints were produced of different metals pairs, both in the waveless and wave modes of welding. In particular, a portable device for butt HVI of copper rods and local stud welding was made and is currently used. In order to increase the plastic deformations in the welding zone, the developers successfully used the technique of abutting the edges of the joined studs in the form of a cone.

Methods of spot HVI using channel systems and water as the couplant appear to be promising. Such systems involve direct flying of the «water shell» onto the cladding plate and its spreading over the area, which is much greater than the cross-section of the barrel, thus eliminating the limitations on the shape and size of the clad surface.

Development of the technique of hydroabrasive cutting of metals promoted development of equipment, which generates water jets of a superhigh velocity (500–1000 m / s, water head of several hundred megapascals). The area of application of this equipment for HVI is limited by a small cross-section of the jets (usually the diameter is several tens of a millimeter, and for the most powerful units it is 1–3 mm). Nonetheless, several works of the German and Arab researchers were published, which studied the effectiveness of application of high-velocity water jets for HVI of thin foils and plates [8–12].

In 1976 a team of researchers of Hannover Technical University, Germany, for the first time reported the application of HVI in cutting of aluminium sheets with water jets at the pressure of 70 to 350 MPa [8]. Welding was performed with a one-time impact of a section of the water jet over the aluminium surface,

Figure 8. Hand gun and accessories for spot HVI (*a*), macrosection (*b*) and microstructure (*c*) of a spot welded joint of steel + brass (×50)

covered with aluminium foil 0.2 mm thick without a welding gap. Diameter of the joint zone was approximately 3 times greater than the sheet thickness (2 mm).

A year later data of a special study of the effect were published, during which high-quality welded joints on aluminium, copper, armco-iron, nickel, lead, zinc and stainless steel were made [9]. The area of welding on the foils 0.2--0.4 mm thick was up to 20 mm^2, and the work of plastic deformation was 2--5 MJ / m^2. Both the wave and waveless modes of spot welding were implemented.

In 1996 a team of researchers from Arab countries undertook similar investigations, using a modification of a hand gun instead of a stationary unit for hydroabrasive cutting (Figure 10, *a*) [11]. The velocity of the water striker, required to form the welded joint was 550 and 750 m / s at nozzle diameters of 5 and 3 mm, respectively.

Figure 10, *b* shows the kinematic scheme of the process of applying the impact and spreading of the water jet over the plate welded to the base (foil), as well as plastic deformation of the plate which occurs in this case. Focal distances (between the nozzle and the surface being welded) were optimized. Optimum modes were determined for welding foils 0.10 to 0.25 mm thick from aluminium, low-carbon and stainless steel to a stainless steel base. The initial gap between the foil and the base varied from 0 up to 2.5 mm. Modes of water jet outflow were determined, which are superlimit modes relative to local welding, and which already lead to perforation of the foils. Paper [11] provides appropriate recommendations on application of HVI technology.

The considered channel systems belong to the small-bore systems and can be used only for the spot HVI of welded-on plates of a limited thickness (foils) and area of the produced joints. In order to improve these indices, it is necessary to use the medium- and large-caliber ballistic channel systems.

As indicated by the data of [13, 14], the first ballistic units were used in HVI investigations by Canadian scientists. They applied a specially designed powder gun of 76 mm caliber, capable of accelerating a light (wood, foam plastic, caprone) tray with the flyer plate (copper of 3.175 mm thickness) fastened on it with up to 800 m / s velocity.

Thus, the above HVI variants are implemented in terms of the classical concepts of EW and collision modes, falling within the usual «weldability window». And still the explosives have a great advantage over the energy sources of HVI, being the source of

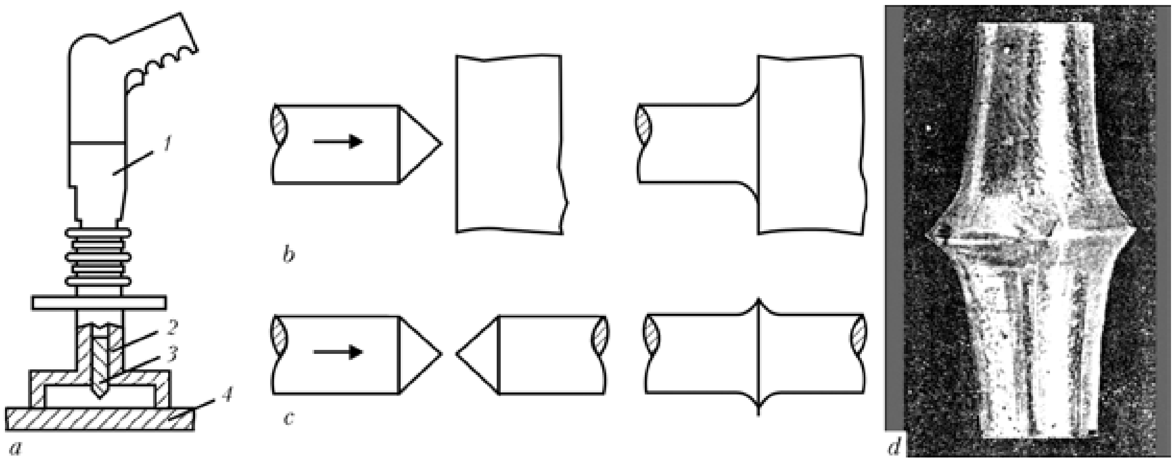

Figure 9. Schematic of a portable device (gun) for HVI of pins (*a*), schematics of the process of stud welding to the base (*b*) and to each other (*c*); *d* ---- photo of butt welded copper studs of 9.5 mm diameter [7]; *1* ---- gun-accelerator for pins; *2* — protective case; *3* ---- stud; *4* — base for welding on the studs

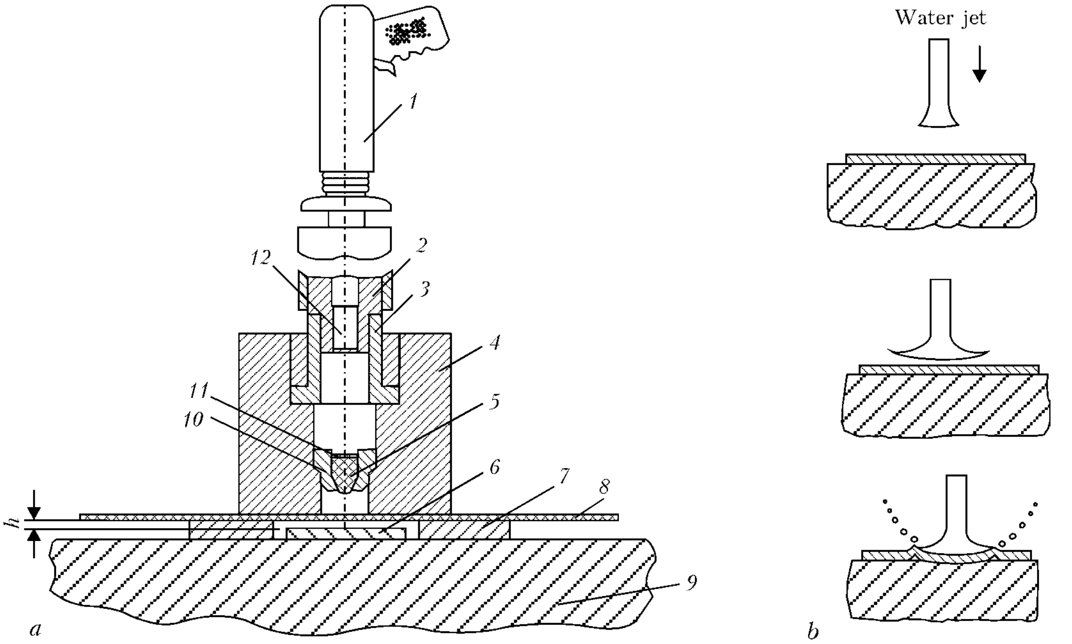

Figure 10. Schematic of a modified design of a water gun (*a*) and kinematic of the process of spot welding by a water jet impact using this gun (*b*): *1* — gun; *2* — channel; *3* — transition piece; *4* — fastener; *5* — water; *6* — base; *7* — gap calibrator; *8* — accelerating plate; *9* — support; *10* — nozzle; *11* — plastic disk; *12* — striker (*h* — welding gap)

power and a large stock of energy and differing by a much greater versatility in solving the practical tasks of EW.

In any case, relatively small-sized items of predominantly soft ductile metals will remain to be the sphere of application of the above technologies of HVI type. Use of EW will remain to be a necessity for high-strength metals and large-sized items. In this connection, let us briefly dwell on the issue of the prospects for organizing the industrial blasting areas and specialized blasting grounds.

Growing requirements to the ecological safety of the technologies already at the end of the previous century led to ousting of the open blasting operations from the cities and closer suburban areas to remote blasting grounds. Making these requirements more stringent will inevitably involve further organizational evolution. Removing the operations in the blasting grounds to a distance of 50–100 km and farther is related to transportation expenses and inconvenience for the personnel. Therefore, a more suitable solution for EW of medium-sized items is establishing in the suburban areas the blasting chambers of an improved design with an automated cycle of loading-unloading and cleaning of the atmosphere. In this relation the E.O. Paton Electric Welding Institute has a unique blasting chamber of a tubular type of the capacity of about 200 kg of explosive in trinitrotolyol equivalent. A similar industrial blasting chamber is being successfully operated at SDB YUZHNOE (Dnepropetrovsk, Ukraine).

Large-scale orders for metal treatment by explosion are more and more often performed in the world now using suitable large natural and man-made structures, namely abandoned mines, tunnels, and port facilities, caves and deserted islands. However, development of this area is restricted by the absence of a sufficient number of orders to provide a continuous workload for large-sized grounds, so that their maintenance is not cost-effective even for a country like Ukraine.

EW theory and practice have already covered a long path of development, however, a number of fundamental problems are still unsolved. This is related to the fact that EW is a complex physical process, which implements the super-high physico-mechanical parameters and for submicrosecond periods induces tremendous gradients of these parameters in small volumes (0.01–0.30 mm). Complexity of analyzing EW processes is such that its investigation can take more than one decade. In this case, it is universally recognized that the most urgent area of further EW studies in the next few years will be investigation of the structure of the «weldability window», particularly of the field adjacent to its lower boundary, as well as searching for the technological methods of influencing the position of the lower boundary.

The following main directions of this search have been outlined so far:

- chemical preparation of the surfaces being joined;
- «prolonging» the time of existence of positive pressure in the zone of joint formation;
- conducting the processes of metal treatment by explosion at an increased initial temperature, etc.

It appears that in the near future it will be possible to implement the EW technologies with performance of a whole range of measures providing for a reliable formation of the joint at low velocities and pressures of the vapour, and, therefore, at much lower loading pulses, degree of elasto-plastic deformation of the processed structures and their elements.

Highly promising is development of the methods of computer simulation of EW. Use of the numeric methods in EW has so far been limited to attempts to simulate the wave formation as a physical phenomenon and development of auxiliary programs for calculation of the optimum modes of EW, particularly for the case of multilayer EW.

There exists the possibility of computer simulation of technological problems of EW with calculation of the fields of stresses and strains in the entire volume of products, which is much less expensive and simpler than the real experiment. Inevitable inaccuracy of the calculations and limited definitions of the model problems are not an obstacle, as after numeric calculation has been performed, selection of the optimum modes requires conducting just a limited number of check experiments.

Application of process modeling has so far been restrained by the cumbersome nature of development and maintenance of special software (need to have one's own small «computing center» in the technological unit). However, these difficulties have been now eliminated, in connection with availability of remote systems and data bases, accessible via the Internet. It is anticipated that during the next 10 to 20 years computer simulation of EW will become a routine technology tool.

As regards the most promising areas of EW application, proceeding from the tendencies which emerged over the last years in the industry both in Ukraine and CIS countries and abroad, the following main areas can be outlined: inner and outer cladding by explosion of long pipes and rods; making flat and tubular electric transition pieces of various types and purpose; improvement of weldability and performance of butt welded joints of high-strength aluminium alloys, using their preliminary or subsequent explosion cladding, as well as other specific tasks that arise in design and manufacture of metal structures when EW is the most widely used and effective process.

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EQUIPMENT OF KZESO COMPANY FOR ARC AND ELECTROSLAG WELDING

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Advanced equipment for arc and electroslag welding and its technological capabilities are considered. Information about technical parameters of serially-manufactured equipment and welding-technological properties of power supply sources is given.

Keywords: *welding equipment, mechanized semi-automatic machines, automatic machines, rectifiers, technical characteristics, technological properties*

Kakhovka plant of electric welding equipment (KZESO Company) is the largest manufacturing and engineering company in Ukraine and CIS countries, specialized traditionally in designing, manufacture, delivery and service maintenance of the advanced electric welding equipment. Products of KZESO are exported to more than 75 countries of the world and to all CIS countries. Permanent staff of the plant, amounting to more than 2300 persons, has a large experience and high professional potential. Here, the most complicated welding machines with the guaranteed quality are manufactured. Thus, the Open Joint Stock Company KZESO is the world leader in the manufacture of equipment for flash-butt welding of rails and pipes, which incorporates the world achievements and which is superior to the foreign analogues.

The plant has available a wide system of technologies for manufacture of any components of electric welding equipment, such as die casting, plastic molding and casting, mechanical treatment of intricate components in specialized installations and electro-erosion machine-tools. There is a complex of equipment for precise stamping and bending of cabinet-type products. Today, the plant list has more than 60 products, namely welding mechanized machines (semi-automatic machines for arc welding), automatic machines for arc and electroslag welding, rectifiers for mechanized and manual welding, machines for resistance spot, seam and flash-butt welding and also the consumer goods. The present article will describe the mechanized machines for arc welding and automatic machines for arc and electroslag welding.

Mechanized machines for arc welding. Machines of the PDG 508M, PDG 508-1 and PDG 516M types (Table 1) with a wide range of adjustment of operating parameters are designed for consumable electrode shielded-gas welding of low-carbon and low-alloy steels using solid and flux-cored wires. When using mixtures on argon base they are also used for alloy steel welding. Machines, equipped with devices for a pulsed welding, are used in making welds in different spatial positions.

Table 1. Technical characteristic of serial welding mechanized machines

Characteristic	*PDG 508M*	*PDG 508-1*	*PDG 516M*	*PDG 603*	*PDF 502*
Rated welding current at 60 % duty cycle and 10 min welding cycle, A	500	500	500	500	500
Ranges of welding current adjustment, A	60--500	60--500	50--500	50--500	150--500
Ranges of arc voltage adjustment, V	18–50	18–50	18–50	18–50	20--45
Diameter of electrode wire, mm:					
solid	1.2--2.0	1.2–2.0	1.2–2.0	1.2–2.5	1.6--2.5
flux-cored	1.2--2.0	1.2–2.0	1.2–2.0	2.0–3.0	2.0--3.0
Ranges of wire feed speed adjustment, m / h	120--1200	140–730	100--1200	98--1012	120--750
Adjustment of electrode wire feed speed	Step	Step	Smooth	Smooth	Smooth
Torch cooling	Natural	Natural	Natural	Water, natural	Natural
Power source	KIU 501	KIO 501	KIO 501	KIO 501	KIO 501
Mass, kg:					
mechanism of wire feed	24	21	17	18	20
power source	275	275	275	275	275

Table 2. Technical characteristic of small-sized welding mechanized machines

Characteristic	*KP 002*	*KP 004*		*KP 016*	*KP 016-1*
Rated welding current, A	140	315	500	315	315
Ranges of welding current adjustment, A	30–140	50–315	60--500	50–315	50--315
Adjustment of arc voltage, V	Step (8 steps)	Smooth		Smooth	Smooth
Ranges of arc voltage adjustment, V	16--22	18--38	18--50	18--38	18--38
Diameter of electrode wire, mm:					
solid	0.6--1.2	0.8--1.4	1.2--2.0	0.8--1.4	0.8--1.6
flux-cored	--	--	1.2--2.0	0.8--1.4	0.8--1.6
Ranges of wire feed speed adjustment, m / h	50–400	80–800		124–1240	100--1100
Power source	--	KIU 501		KIU 301	KIU 301
Mass, kg:					
feeding device	--	16		9	10
electrode wire	12	12		5	5
power source, in total	75	275		205	205

In the design of the PDG 603 type mechanized machine (Table 1) a water cooling of a torch and also a portable control panel, providing switching over of two preset welding conditions and their smooth setting up, are envisaged for heat removal in welding at increased condition parameters. Active consumed power of the machine from mains with allowance for duty cycle depends on supply source: 8.7 (KIU 301), 18 (KIU 501), 9.6 (KIG 401), 22.6 kW (KIG 603).

The specialized machine of the PDF 502 type (Table 1) is designed for submerged arc welding, using a bath method, of reinforcement of concrete structures using steel solid and flux-cored self-shielding wire. Control circuit provides operation in the condition of a conventional mechanized machine, and has also a feasibility to switch on successively the first, second and third conditions during the welding cycle directly from the working site of the welder.

Except the above-listed five serial welding mechanized machines, four small-sized machines of KP 002, KP 004, KP 016 and KP 016-1 type have been developed at the plant over the recent years (Table 2). Machine KP 002 represents a single unit of a wire feed mechanism with a power source. It is equipped with wheels for movement and has a platform for cylinder. Unlike other machines, machine KP 002 has 220 V rated voltage of a single-phase AC mains. Ranges of welding current adjustment in KP 002 are 30–140 A, electrode wire feed speed is 50– 400 m / h.

The adjustment of electrode wire feed speed in all the KP machines is smooth. In machine KP 016 the control circuit provides feasibility of switching two preset conditions of welding directly from the working site. Machine KP 016-1 (Figure 1) is equipped with a microprocessor control system with a digital indication of wire feed speed. The machine design envisages the torch connection to the European connectors. The same features are also typical of the new generation of machines KP 009 and KP 010, which have found the wide spreading in automotive industry of Russia and Ukraine.

In collaboration with German company GLOS the Kakhovka plant has mastered the manufacture of three new types of welding mechanized machines GLC 356-C, GLC 451-C (Figure 2) and GLC 456-C. They are equipped with the CK 68-C type mechanism of wire feeding having a step adjustment of the welding voltage. Machines GLC 356-C and GLC 451-C have a synergic system of control. When selecting any combination of parameters of welding conditions, material, wire diameter and shielding medium, the system of control sets automatically the speed of electrode wire feed. When presetting the wire feed speed or thickness of metal to be welded the indicators at the control panel indicate the optimum position of step switches, and also the expected welding current. The control system allows setting and maintaining ten welding conditions for different diameters of wire and materials. Conditions are set in any sequence that reduces the time of equipment resetting.

The peculiar features of welding mechanized machines of a joint manufacture is the widened range of electrode wire feed speed (0–1440 m / h), the feasibility of its smooth adjustment and also a wide range

Figure 1. Mechanized machine KP 016-1

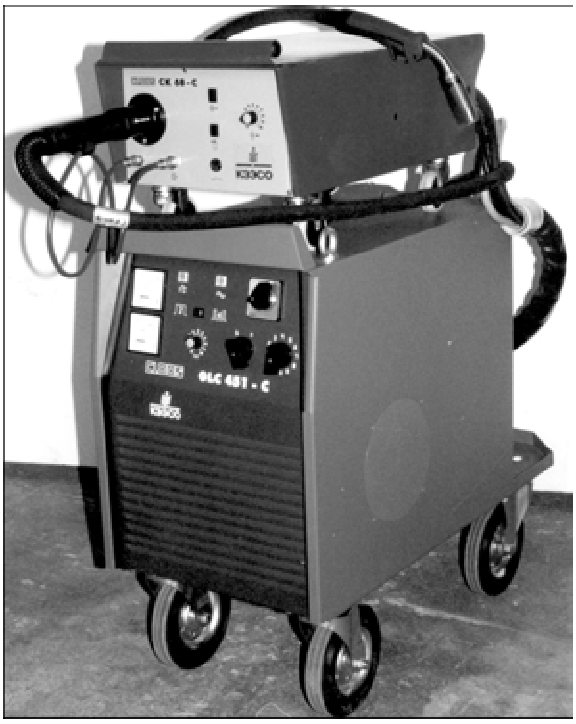

Figure 2. Mechanized machine GLS 451-C

of changing the electrode wire diameter (0.8–2.0 mm).

Welding rectifiers. Requirements to the delivery set of equipment for mechanized welding demanded for the development and manufacture of a range of welding current sources operating within 50--1250 A at the KZESO Company.

Welding rectifier GART 160 of the KI 001 type is designed for manual arc welding and cutting of low-carbon and alloy steels, non-ferrous metals and alloys. Welding is performed with coated electrodes at direct current of straight and reverse polarity. It is used in industry and agriculture, in maintenance stations and daily life. Rectifier has a system, facilitating the arc ignition and stepless adjustment of welding current. Technical characteristic: rated welding current is 125 A at duty cycle 20 % and 5 min welding cycle; 20--160 A ranges of current adjustment; 21–26 V ranges of operating voltage adjustment; 1.5--4.0 mm diameter of electrodes; 45 kg mass; 450 × 235 × 360 mm dimensions.

Figure 3. Welding rectifier KIU 501

Table 3. Technical characteristics of rectifiers

Type of rectifier	*Ranges of current adjustment, A*	*Duty cycle, %*	*Mass, kg*
KIU 301	50–315	60	205
KIU 501	50–500	60	275
KIU 1201	200–1250	100	550

At the present time, the domestic consumers demand mainly for thyristor power sources that is stipulated by simplicity and its low cost, high reliability and repairability.

Universal welding rectifiers (Table 3) KIU 301, KIU 501 (Figure 3) and KIU 1201 are designed for mechanized and automatic shielded-gas arc welding, submerged arc welding and with rod electrodes of all types.

Welding rectifiers KIG 401 (50--400 A) and KIG 601 (60–630 A) serve mainly for mechanized arc shielded-gas welding. Step switching of welding voltage makes it possible to cover the wide range of welding currents without use of complex electron devices. Special scheme of rectifying provides the welding current with a very low coefficient of pulsation. Both rectifiers are simple in service and reliable in operation.

Numerous experiments on improvement of welding properties of thyristor power sources were finalized by the selection of optimum parameters of the choke and separate coefficients of amplification in links of the schematic diagram. It was taken into attention that the good welding properties in the entire range of currents were obtained, as a rule, at a stable process of welding at low currents. The most radical measure for improvement of welding properties of power source is the reduction in rate of current increment in electrode metal drop. For this purpose, the increase in inductance of choke from 1.0–1.4 mH and introduction of derivative from welding current into the law of control of conductivity angle of a thyristor group was recommended. The application of derivative from welding current di / dt (D-component) into the control circuit of power sources allows obtaining optimum operating parameters and high stability of the welding process.

Technological properties of welding mechanized machines and rectifiers. The above-described welding equipment has passed the industrial trials at the leading enterprises of machine-building and shipbuilding industries. Integrated investigation of weld-

Table 4. Technical characteristic of welding automatic machines

Characteristic	*À 1406*		*À 1412*	*À 1416*	
	500 À	*1250 À*		*500 À*	*1250 À*
Rated welding current, A:					
at 60 % duty cycle	500		1250 × 2	500	
at 100 % duty cycle	1250			1250	
Ranges of welding current adjustment, A	60–500	250–1250	250–1250	60–500	250–1250
Number of electrodes, pcs	1		2	1	
Diameter of electrode wire, mm	1.2–2.0	2.0–5.0	3.0–6.0	1.2–2.0	2.0–5.0
Ranges of electrode wire feed speed adjustment, m / h:	17–553				
1st range			15–149	47–509	
2nd range			58–583	Step	
Ranges of welding speed adjustment, m / h:					
1st range	–		12–60	12–120	
2nd range	–		50–250	Step	
Power source	KIU 501	KIU 1201	KIU 1201 × 2	KIU 501	KIU 1201
Mass, kg:					
welding head	185		400	320	
power source	275	550	550	275	550

ing-technological properties of mechanized and automatic machines was made at the E.O. Paton Electric Welding Institute (under the supervision of Prof. N.M. Voropaj) in accordance with GOST 25616–83. The following characteristics of welding machines and appropriate power sources were evaluated: reliability of welding process setting; metal losses for spattering and fumes; quality of formation of welds.

Electrical parameters of welding conditions in CO_2 and Ar + 20 % CO_2 mixture were recorded using a control-simulator which provides a current digital indexing of values of arc voltage and welding current, and also the change in averaged values of duration of arc gap short-circuiting. Stability of welding process was defined by the number of initial short-circuits or arc breaks occurring from the moment of the first wire contact with a sample until establishing a stable process. To define the technological properties, eight most typical conditions of welding 3–16 mm thick metal were selected.

Analysis of results of technological tests showed that equipment of KZESO ensures almost instantaneous arc exciting (after one-two wire contacts with the sample surface). By the degree of reduction in metal losses for spattering and duration of short-circuits this equipment is most effective. Welds, made by welding machines of series KP, are characterized by a uniform formation, smooth and fine-ripple surface and smooth transitions to the parent metal. Important technological advantage of the welding equipment under the consideration is the sufficiently stable arc burning in welding at low currents (40–50 A) and application of electrode wire of an increased diameter. Since 1997 the KZESO has mastered the manufacture of welding rectifiers with a rated current of 500 A. At present, the industrial manufacture of rectifiers for 315 A (KIU 301) and 1200 A (KIU 1201) has been mastered. The latter can be used as a many-station source in a set with ballast rheostats.

One of the new developments made by KZESO in collaboration with Design Office of the Paton Institute is the multi-purpose universal rectifier KIU 701 with unique technical solutions as to the power part and control and monitoring system. It is characteristic that the mentioned source has an increased open-circuit voltage, and also feasibility of a smooth increment of current value in the process of welding.

Automatic machines for arc welding. Automatic machines of the A 1406, A 1412 and A 1416 types (Table 4) are designed for arc welding and surfacing of low-carbon and alloyed steels. Automatic machine A 1406 is mounted on surfacing machine-tools and ensures surfacing in shielding gas, with open arc using flux-cored wire and strip, submerged arc surfacing, with open arc using a split electrode. Suspended self-propelled automatic machine A 1416-1 (Figure 4) of a modular design with a laser system of weld tracking is designed for submerged arc welding of long longitudinal welds made from low-carbon and alloy steels. Welding, as a rule, is performed at direct current at electrode wire feed speeds and welding speeds independent of arc parameters. The automatic machine is designed using an advanced element base with use of sub-assemblies and components of the leading European manufacturers. The automatic machine is controlled by using controller of Siemens Company. Presetting of parameters and control of operation of mechanisms is performed both from the control panel,

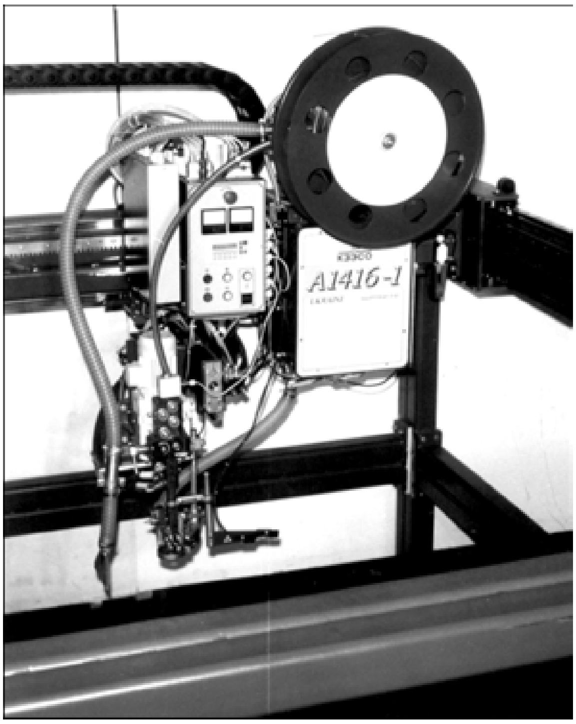

Figure 4. Self-propelled automatic machine A 1416-1

mounted on a welding head, and also from the panel arranged in a control cabinet.

The nozzle positioning to the butt of sheets is made in manual and automatic conditions using light points from beams of tracking sensors. Gap between sheets in welding without edge preparation should be 1.5–2.0 mm.

Automatic machines KA 001 and KA 002 of a tractor type are designed for arc welding of butt joints under flux with and without edge preparation (number of electrodes — 1; electrode wire diameter — 3–5 mm; ranges of welding current adjustment — 250–1000 A; ranges of electrode wire feed speed adjustment — 49–404 (KA 001) and 30–300 m / h (KA 002). Both automatic machines are completed with the KIU 1201 type power source.

Suspended self-propelled automatic machine AD 231 is used for a wide range of surfacing jobs at 250–1250 A current (number of electrodes — 1; wire diameter — 4–6 mm; wire feed speed — 46–460 m / h).

Automatic machines for electroslag welding. The automatic machines A 1304 (Figure 5) and A 535 are manufactured for electroslag welding. The automatic machine A 1304 is designed for electroslag consumable electrode welding of products made from steel, aluminium and its alloys. Rated welding current at 100 % duty cycle is 3000 A (A 1304), 6000 A (A 1304-03), 9000 A (A 1304-06) (number of wires for the latter three automatic machines — 4; diameter of wires for A 1304 is 3 mm, for A 1304-03 is 3 and 5 mm, and for A 1304-06 is 3.5 and 6 mm. All three automatic machines A 1304 are completed with welding transformers of the TRMK-3000-1 type.

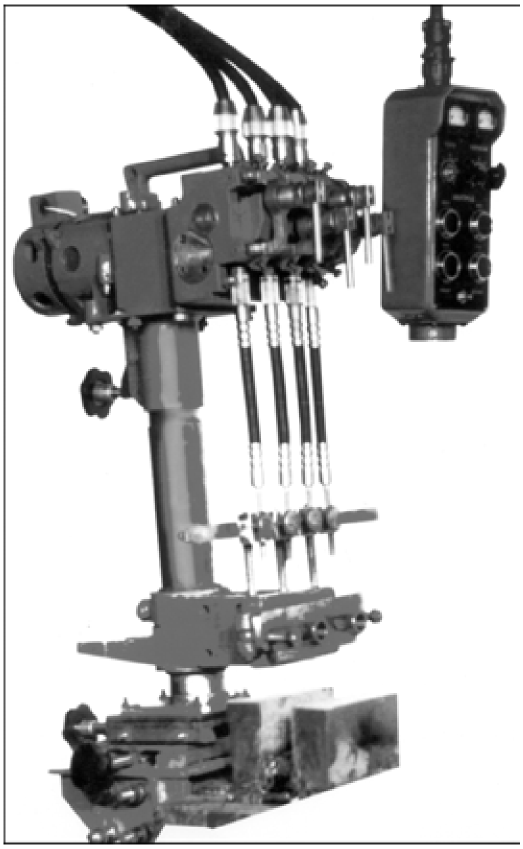

Figure 5. Automatic machine A 1304 for electroslag welding

Automatic machine A 535 is designed for a single-pass electroslag welding with a double-sided formation of welds of up to 450 mm thick steels. This machine can realize welding of longitudinal and circumferential butt welds, fillet and T-joints. Rated welding current at 80 % duty cycle is 1000 A; at 100 % duty cycle — 900 A; number of 3 mm diameter wires is 3; power source — welding transformer TShS1000-3.

OJSC KZESO has a closed cycle of production: from casting up to «key turn» manufacture with starting-setting works. The advanced technologies, multiplied by power of technical equipment and highly-qualified staff of specialists is the pledge of success of the enterprise. The widening of volumes of production of competitive equipment and close collaboration with the E.O. Paton Electric Welding Institute allows KZESO to face the future with optimism.

NEW GENERATION OF EQUIPMENT FOR AUTOMATED ULTRASONIC TESTING OF WELDED PIPES

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Installations of the new generation for automatic ultrasonic testing, designed using sophisticated elements of mechanics and electronics, are presented. Using this equipment, the testing of welds and end areas of pipes of diameter from 508 to 1420 mm and thickness from 7 to 50 mm can be realized.

Keywords: *welded pipes, mass production, non-destructive testing, automated ultrasonic testing, installations, weld metal*

Nowadays, the requirements to welded pipes, used in construction of main pipelines, in particular to their service reliability, are growing continuously in the world. In competition for the markets, the pipe plants, in spite of large expenses, have to use the most sophisticated equipment for the automatic ultrasonic testing (AUST) to provide a reliable detection of possible defects in welds and end areas of pipes and, thus, to guarantee the high quality of products.

Open Joint Stock Company «Vyksunsk Metallurgical Works» (VMZ), having a many-year experience of collaboration with the E.O. Paton Electric Welding Institute, considers the mastering of production of pipes for main pipeline, corresponding to the requirements of American Petroleum Institute (API) to be one of its priorary tasks. However, it is impossible to solve this task without use of the advanced equipment for AUST of welds and end areas of pipes as one of the constituents guaranteeing the requirement of standard API Spec. Q1.

In October, 2003, the VMZ invited the Design Office of the Paton Institute to participate in the tender for delivery of the following equipment:

• two installations for AUST of end areas of pipes of 508--1067 mm diameter and 7–34 mm wall thickness;

• installation for AUST of longitudinal welds of pipes of 508--1420 mm diameter and 7–50 mm wall thickness;

• three installations for AUST of longitudinal welds of pipes of 508–1067 mm diameter.

In spite of limited terms of the equipment delivery, the decision was taken to participate in the tender in cooperation with the old partner from NIINK «Introskop» (Republic of Moldova), the supplier of the multichannel ultrasonic equipment.

The conditions of tender were very strict. By the customer's requirement, the application for participation had to contain the detailed description of configuration of control system, sketch project of the installation designed, scheme of sonic test, description of automation level, main technical characteristics of the acoustic part.

In addition, a basic information was required about a possible supplier of equipment, including information about main types of earlier supplied products for AUST (Table 1); list of customers of these products (Table 2); experience in cooperation with VMZ.

As is seen from Tables, the associates of Design Office of the Paton Institute had a sufficient experience in works of this direction. The complex NK 180 for AUST (6 units) was designed for VMZ and delivered in the 1989–1990.

Table 1. Main types of products manufactured over the recent years for UST and eddy-current control (ECC)

Type of product	*Main modifications and characteristics*
NK 106	8 US channels, testing of longitudinal welds of 530--1429 mm diameter pipes, 800 kg mass
NK 147	4 US channels, testing of bimetal of components of rockets, 350 kg mass
NK 148	4 US channels, testing of welds of rocketry, 450 kg mass
NK 164	8 US channels, testing of welds of rocket bodies, 300 kg mass
NK 193	8 US channels, testing of welds of NPS pipings, scanner mass is 30 kg
NK 300	4 US channels, testing of welds of fuel channels of RBMK-1000, 150 kg mass
NK 310	8 US channels, testing of circumferential welds of main pipelines, 250 kg mass (experimental model)
NK 321	8 US channels, testing of circumferential welds of NPS pipings, mass of scanner is 15 kg
NK 331	ECC of bridges of collectors of NPS steam generators, 50 kg mass

Table 2. Main consumers of products

Type of product	*Consumer*
NK 147, NK 148, NK 164, AUST	«Yuzhmashzavod», Dnepropetrovsk
NK 193, NK 300, NK 321, NK 331	Chernobyl NPS, Zaporozhie NPS
NK 310, AUST of main pipelines (experimental model)	NEK «Ukrtransgas»
NK 106, UST of pipe welds	Khartsyzsk Pipe Works

Tender was realized in two stages. At the first stage (by correspondence) all received applications were analysed by the following criteria:

• conformity of characteristics of offered products to technical requirements of VMZ Company;

• economical efficiency of products (price–quality ratio);

• cost characteristics and attractiveness of payment conditions;

• reputation of company.

From the results of analysis of applications for participation in the second (real) stage of tender, the following organizations were invited: «Altest» (Moscow); «Konstruktsiya, Ltd.» (Moscow); Design Office of the Paton Institute (Ukraine) together with NIINK «Introskop» (Republic of Moldova); KARL DEUTSCH (Germany); ScanMaster Systems (Israel); INDURO Krautkramer, the representative of AGFA NDT GmbH (GE Inspection Technologies GmbH, Germany).

At the second stage the presentations of representatives of organizations participating in the tender were made. From the results of meeting of the tender committee the Design Office of the Paton Institute

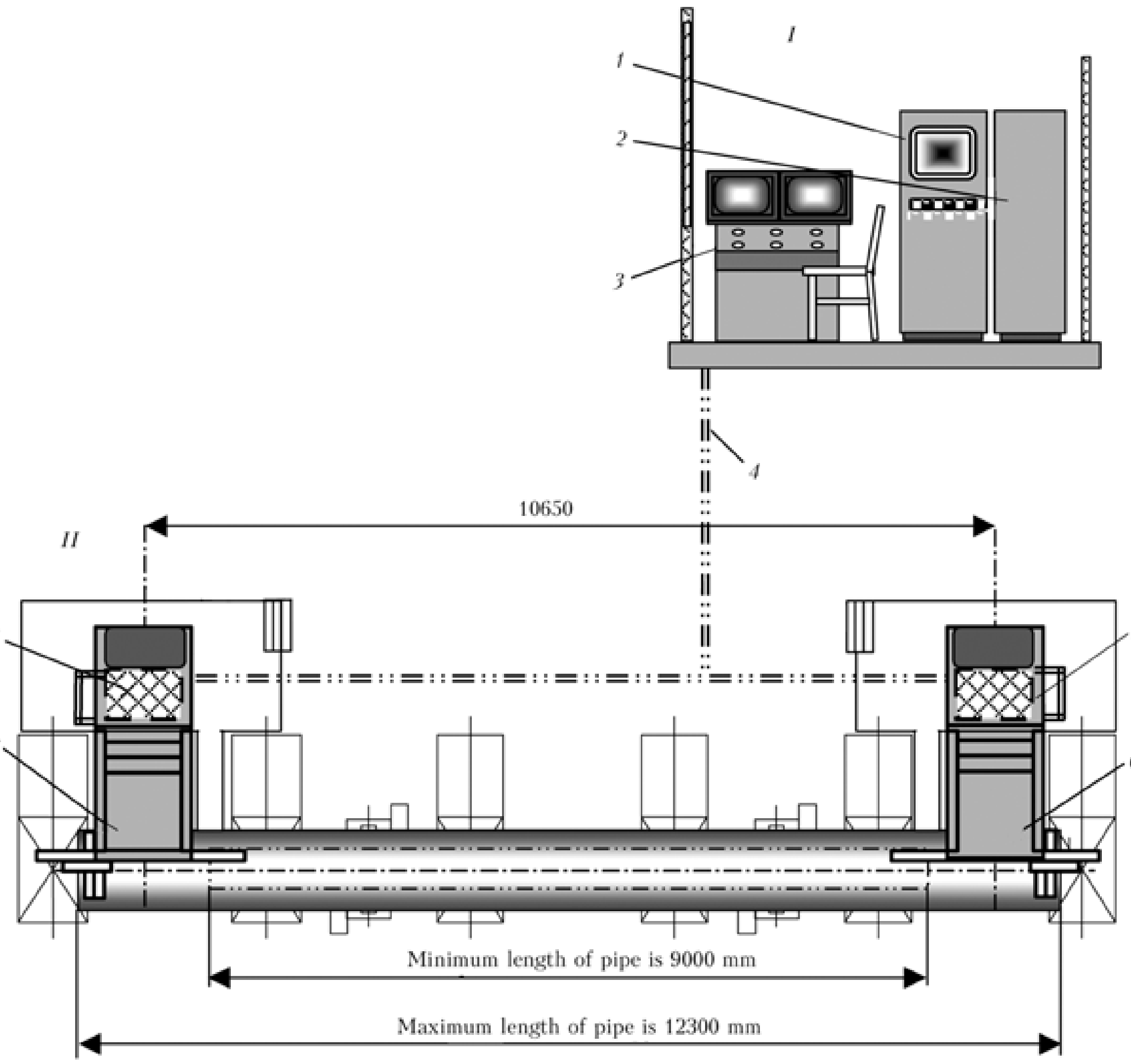

Figure 1. Scheme of installation NK 362 for AUST of end areas of pipes of 508–1067 mm diameter: *I* — cabin of remote control operator; *II* — arrangement of unit on roller conveyor (plan view); *1* — multichannel US flaw detector; *2* — control cabinet; *3* ---- control panel with TV monitors; *4* — cables connections; *5* — power control cabinet; *6* — units of AUST of end areas of pipes with acoustic heads

was recognized to be the main supplier of equipment and the contract was signed for the delivery of six AUST installations.

The first installation NK 362 for AUST of end areas of 508–1067 mm diameter pipes (Figure 1) has already passed the functional tests in the presence of the customer representative. Two more installations, including NK 360 for AUST of longitudinal welds of pipes of 508–1420 mm diameter and 7–50 mm wall thickness (Figure 2) are at stage of assembly.

Strict requirements for resetting in transition for testing pipes of another type and size (time of resetting and establishment of operation condition should not exceed, respectively, 30 and 10 min), and requirements for safety of the AUST system defined the architecture of control system of the installations. The control system is realized using the Siemens programmable controller Simatic S7-300 with two distributing stations ET-200m. The installations are controlled using mains PROFIBUS-DP, manual control — from the Siemens programmable panels OP-17. Servomotors of standard drives of Rexroth Bosch Company are used in all installations. Interface of control units is made using drives PROFIBUS-DP. Both installations (NK 360 and NK 362) are designed by a modular principle and consist of similar sub-assemblies.

The base assembly unit of the installations, providing the feeding of acoustic blocks for the position of testing, is a load-carrying module of a vertical displacement, whose rigidity of design serves for guarantee of stability and repetition of results of US testing. Modules of a horizontal movement are mounted on the load-carrying module. Installation NK 360 includes a system of laser tracking the weld reinforcement bead on the base of industrial computer, developed at the Paton Institute. Acoustic blocks with US heads are mounted on the modules of horizontal movement, each of them has its pneumatic drive of lifting and lowering, ensuring a reliable clamping to the pipe surface. In addition, the manual drives for adjustment of distance between US heads in setting are mounted on the modules of a horizontal movement. The installations are completed with track sensors (NK 360 — of longitudinal displacement, NK 362 — of pipe rotation), paint marker of defects, device of wetting. External individual container with paint, being under pressure, is used for each paint marker. Detection of defects, processing of UST data, record of results of calibration are realized by multichannel US flaw detector supplied by NIINK «Introskop» (Republic of Moldova).

All the components of installations are controlled by controller «Simatic S7-300», and the multichannel flaw detector is controlled by its technological computer. Conversion of signals and their record into a buffer memory of ADC is performed according to program-set time strobe. Identification of defects, computation of their parameters and coordinates are made

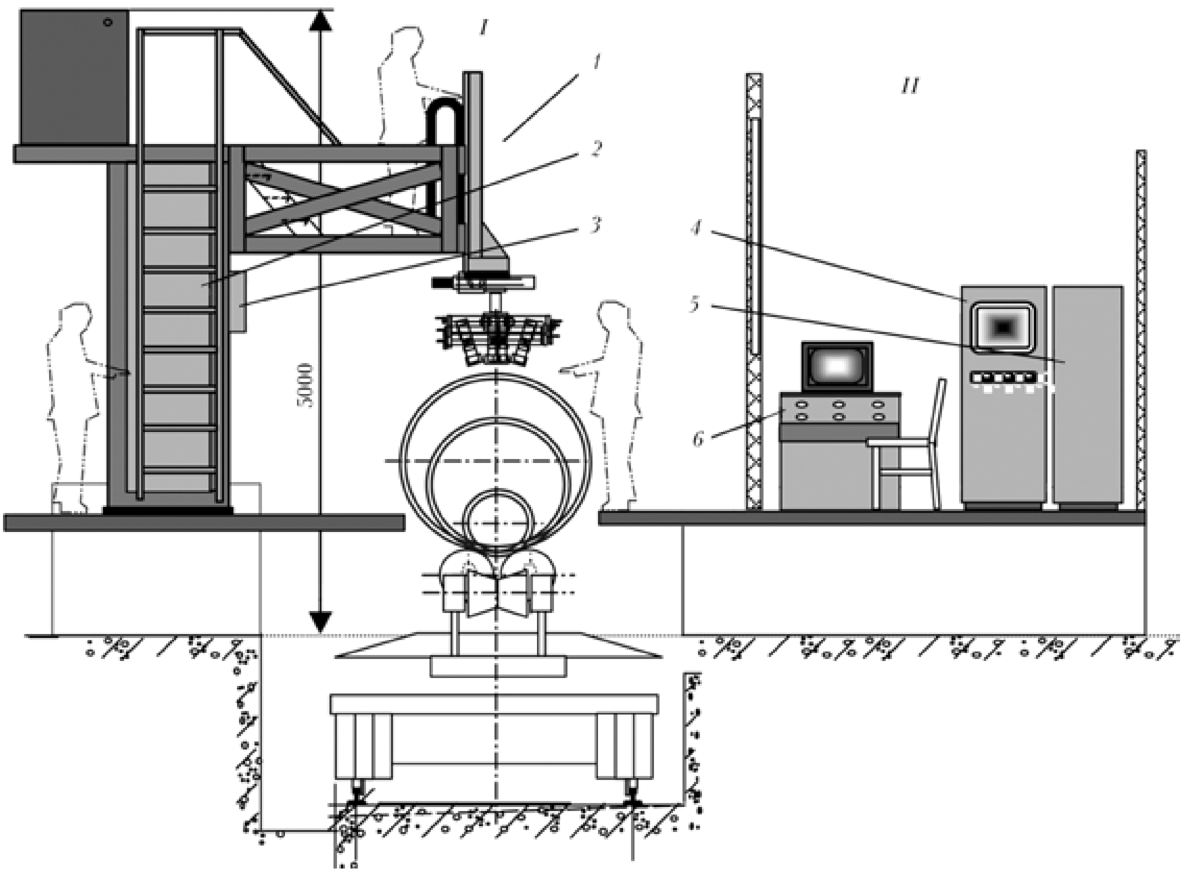

Figure 2. Scheme of installation NK 360 for AUST of weld of pipes of 508–1420 mm diameter: *I* — arrangement of installation in line of testing (side view); *II* — operator's cabin; *1* — technological unit of AUST; *2* — power cabinet; *3* — panel for conditions setting; *4* — multichannel US flaw detector; *5* — control cabinet; *6* — control panel with TV monitor

as a result of analysis and processing of signals accumulated in ADC memory. Using the obtained information, record of defects and display of their parameters on the monitor screen are realized.

Cycle of testing is represented on the monitor screen, that allows operator to record the current results of testing with a feasibility of display of A-scanning on the screen by one of the operating channels. Result of AUST is the file of defects, placed into database, and protocol of testing, dumped to a printer. There is interface for exchange of information from ACS TP of the shop.

System of AUST, designed in installations, makes it possible to

• program and memorize parameters of conditions of operation and setting of sensitivity, to change quickly the control program (rate, path) and also the setting parameters;

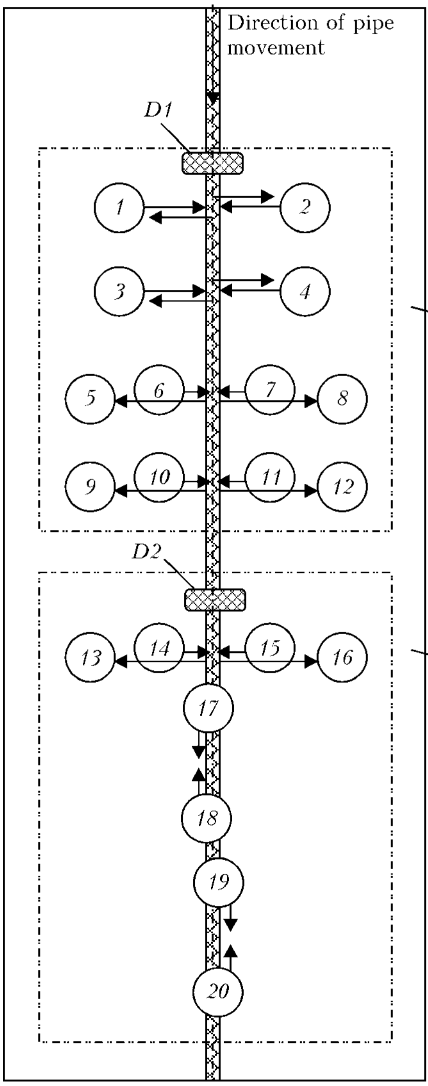

Figure 3. Scheme of arrangement of piezo-electric transducer for testing longitudinal welds of pipes of 508–1420 mm diameter and 7–50 mm wall thickness: *D1* and *D2* — laser sensors for tracking the weld reinforcement bead; *1–4* — group of inclined US transducers; *5–16* — US transducers operating in tandem schemes; *17–20* — US transducers mounted on weld and operating in an immersion variant for detection of transverse defects

• realize different acoustic schemes and to control the acoustic contact;

• realize acquisition and processing of data without participation of operator of UST, thus providing the objective results of testing;

• control the US parameters and operation of mechanisms by data displayed on the screen.

Main technical characteristics of installation NK 362 for AUST of end areas of pipes of 508–1067 mm diameter and 7–34 mm wall thickness

Operating frequency, MHz	2.5; 4.0
Linear rate of testing, m / min	max 20
Range of rate adjustment	not less than 1--100
Number of US channels, pcs	20
Sensitivity factor in channels at dynamic condition, dB	not worse than 12
Non-tested zone in weld region, mm	not more than 15
Non-tested zone at ends of pipes, mm	not more than 10
Adjustment of acoustic gap, mm	0–5
Water consumption, l / min	not more than 50
Consumed power, kV·A	not more than 8

Installation provides per one pipe rotation the sonic test around the entire perimeter of ends of pipes across the wall thickness, revealing defects of lamination type in 60 mm width from the edge and longitudinally-oriented defects of crack type in width 30 mm from edge; automatic control of quality of acoustic contact in all the defectoscopic channels.

Installation guarantees the efficiency of testing end areas of pipes of not less than 25 pipes per hour.

Sensitivity of system is sufficient for automatic detection of the following defects:

• of lamination type, whose amplitude of echo-signal is equal or exceeds the echo-signals from artificial reflector in the form of drilling hole with a flat bottom of 5 mm diameter;

• of longitudinal crack type, whose amplitude of echo-signal is equal or exceeds echo-signals from artificial reflectors in the form of rectangular longitudinal slots of 1 mm width, 50 mm length and depth of 5 % of wall thickness, made on external and internal surfaces of pipes.

Main technical characteristics of installation NK 360 for AUST of longitudinal welds of pipes of 508–1420 mm diameter and 7–50 mm wall thickness

Operating frequency, MHz	2.5; 4.0
Rate of testing, m / min	max 30
Range of rate adjustment	not less than 1--100
Number of US channels, pcs	24
Frequency of probing pulses in each channel providing sending pulses per 1 mm of weld length	not less than 2
Sensitivity factor in channels at dynamic condition, dB	not worse than 12
Not-tested zone at pipe ends, mm	not more than 30
Accuracy of tracking weld reinforcement bead in horizontal plane, mm	± 0.5
Adjustment of acoustic gap, mm	0–5
Water consumption, l / min	not more than 50
Consumed power, kV·A	not more than 8

Installation provides sonic test of weld across the thickness pipe wall from both sides of weld, revealing different-oriented (longitudinal, transverse and other) defects; automatic control of quality of acoustic contact in all the flaw detection channels.

Sensitivity of the system is sufficient for automatic detection of weld defects, whose amplitude of echo-signals is equal or exceeds the echo-signals from artificial reflectors in the form a rectangular slot of 1 mm width, 50 mm length and depth of 5 % of pipe wall thickness, a through hole of 1.6 mm diameter in weld, a rectangular slot, made across the weld, of depth of 5 % of pipe wall thickness.

Time instability of the installation by each channel should not exceed 2 dB for 8 h of continuous operation.

Figure 3 shows a variant of scheme of acoustic control and arrangement of piezo-electric transducers in realization of process of AUST of welds.

Number of operating tandem blocks depends on wall thickness. At 50 mm wall thickness all tandem schemes are operated. Control is realized in an immersion variant.

This solution replaces X- and K-shaped schemes and prevails at present in foreign installations for testing.

For all the installations, the following things are envisaged:

• deposition of marks of different colour on pipe surface, defining the type and location site of defects, and also areas with insufficient acoustic contact;

• protocol of testing is issued for each pipe, including at least the number of pipe, amplitudes of echo-signals of detected defects with indication of their coordinates, length, number of channel, detected the defect;

• in recording the testing results the defectogram of each channel is recorded to have a feasibility of reviewing or printing the information of all or part of channels on paper carrier;

• calibration is made on standard samples of enterprise, i.e. simulators of defects, both in static and dynamic conditions at the rate of their displacement close to the rate of movement (rotation) of pipes in the process of testing. Results of calibration are recorded;

• the installation provides the transfer of information about testing results into the system of ACS TP of the shop by a local mains.

In the near future the service of installations NK 362, NK 360 at OJSC VMZ will show the degree of justification of our ambitions on the creation of advanced equipment of AUST of pipes under the conditions of their mass manufacture. We are looking forward to the positive result and ready to cooperate with pipe plants of Ukraine and other countries.

COOPERATION BETWEEN NKMZ AND PWI IN THE FIELD OF ELECTROSLAG WELDING FOR HEAVY ENGINEERING APPLICATIONS

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Results of many years of cooperation between NKMZ and PWI in the field of production of large billets using electroslag welding are presented. Examples of successful application of ESW for the fabrication of critical pieces of equipment and specific components are given. Potentialities and prospects of further improvement of the ESW technologies applied in heavy engineering are shown.

Keywords: *structural materials, electroslag welding, heavy engineering, enlargement of billets, specialised units, welding devices*

Technical progress in heavy engineering, being the basic industrial sector, determines the possibility of accelerated development of the entire machine-building area, metallurgy and other critical industries.

In a period of the 1960s to 1980s NKMZ (Novo-Kramatorsk Machine-Building Plant) commercialised production of super large machines and units, the fabrication of which required the use of new special technologies to provide unique billets up to 300 t in weight. It was a government task, which was handled by the Plant through using an approved promising area, i.e. enlargement of billets by making them forged-welded or cast-welded using forgings or castings of a comparatively small weight, welded using rolled stock, or combined. Fundamentally new welding processes were needed to enlarge massive billets. One of them was electroslag welding, an outstanding domestic invention made by the E.O. Paton Electric Welding Institute of the NAS of Ukraine. ESW allowed permanent joints of almost unlimited thickness to be made in a single pass [1]. NKMZ became a pioneer in commercialising this welding method. The joint work started in the 1950s is still in progress.

From the very beginning, all theoretical and experimental studies on the development of ESW were supervised by Prof. B.E. Paton. Principles of the electroslag process were developed and practical recommendations for its wide commercial application were worked out owing to the efforts of a pleiad of eminent scientists of the E.O. Paton Electric Welding Institute, such as G.Z. Voloshkevich, D.A. Dudko, A.M. Makara, Yu.A. Sterenbogen, I.I. Sushchuk-Slyusarenko, I.I. Lychko, as well as many other specialists.

Successful application of the new ESW methods would be impossible without a creative union of the PWI scientists and technologists of the Chief Welding Department of the Plant, and first of all I.G. Guzenko, V.V. Chernykh, G.G. Mejramov, V.S. Pogorelov, L.P. Eregin, V.M. Semyonov, A.E. Malaj, A.D. Panin, V.P. Gulida, I.S. Savchenko, etc. Many of them became famous scientists and prominent managers of welding production in heavy engineering. An invaluable contribution to commercialisation and practical application of the ESW technology and equipment was made by electric welding operators, such as A.I. Imshenetsky, V.Ya. Tsybulenko, P.E. Nazarenko, N.G. Shevchenko, A.V. Yarmolenko, V.K. Lugovskoj, V.I. Glushchenko, A.S. Korkh, V.M. Shurmalev, etc.

As a result of cooperation between NKMZ and PWI, for the first time in national machine-building the Plant in 1951 pioneered in applying ESW using wire electrodes to weld blades to stators of hydraulic turbines with thickness of the parts welded equal to 200 mm. For this purpose the Institute manufactured special double-electrode devices A-316, which later on were replaced by the three-electrode ones A-372.

By 1954 the Plant had mastered the manufacture of beds of mechanical forging-stamping presses with a force of 40 MN and hydraulic turbine shafts by using ESW. The output of the Plant continuously increased. NKMZ manufactured beds and cylinders of presses with a force of 750 MN for the Kujbyshev Metallurgical Works (now — Open Joints Stock Metallugical Company «Siberian Aluminium», Samara, Russia) and Verkhnyaya Salda Metallurgical Works, a series of hydraulic turbine shafts for Gorkovskaya, Bratskaya, Assuan (Egypt) and Krasnoyarskaya hydroelectric stations, as well as a bed of press 6300. The ESW technology and equipment available at that time limited thickness of the metal welded to 400 mm and did not allow welding of parts of complex configuration, which gave no way of their more extensive application.

To widen the range of thicknesses welded, a new method for making permanent joints in metal billets was developed in 1956 owing to the joint efforts of the PWI and NKMZ specialists. This method was called consumable-nozzle electroslag welding [2]. It allowed welding of sections of almost unlimited thickness and length, as well as of complex configuration. An incentive to the development of this ESW method was the need to weld hydraulic turbine blades more than 200 mm thick, the mating cross sections of which were drop-shaped [3]. The first practical application of consumable-nozzle ESW was to repair defects of large castings, which before had been discarded at the Plant.

Wide capabilities of the ESW method [4] attracted attention of designers and technologists of the Plant, who encouraged the use of non-traditional approaches to selection and development of new design and technology solutions to manufacture large parts for machines and units of press-forging, rolling, power generation and other types of equipment.

Substantial increase in scopes of application of ESW required manufacture of an improved welding equipment to make electroslag joints. Designers of the Institute headed by B.E. Paton successfully worked on the development of the ESW devices, which differed in principle from the electric arc welding devices. Worthy of special notice is the contribution made by P.I. Sevbo, M.G. Belfor, R.I. Lashkevich, V.B. Smolyarko, I.V. Yushchenko, V.A. Maslov, etc.

The positive experience of using ESW at NKMZ allowed the Institute to design and manufacture a series of devices for welding using wire electrodes, such as the improved three-electrode device A-535 (instead of A-372) and small-size devices A-433 and A-790. 6-electrode devices A-645 (used for the first time for ESW of arches of large excavator buckets and hard-to-reach joints in a spreader beam of press 6300) and 18-electrode devices A-741 equipped with the increased-intensity power supplies TShS-3000-3 were manufactured for implementation of consumable-nozzle ESW. Device A-550 was made for welding using plate electrodes.

Much success was achieved during that period in improvement of the circumferential ESW equipment. Upgrading of the available unit resulted in the manufacture of a mechanised roller-type rig and welding device equipped with two three-electrode welding heads A-1247, allowing fast (10–15 s) automatic replacement of a faulty head by the other (stand-by) one with no violation of the welding process. The gantry-type stationary unit with the automatic device A-741 for consumable-nozzle ESW located on the spreader beam of which was designed and manufactured for welding parts up to 2500 mm thick. Also, the unit was fitted with two balconies located opposite to each other and equipped with devices A-372. The balconies with the devices were made with a possibility of moving in horizontal and vertical directions to ensure support and visual inspection of the consumable-nozzle ESW process and perform off-line wire-electrode ESW of parts up to 450 mm thick. The ESW bays were arranged in workshops comprising hoisting equipment of a limited load-carrying capacity. Workstations in other workshops of the Plant, where parts up to 300 t in weight (beams, beds, anvil blocks, spreaders, etc.) could be welded, were arranged for that purpose. Portable multiple-electrode feed mechanisms A-480 were designed and manufactured for welding such parts.

Carbon steels of grades 30 and 35 were primarily used for the fabrication of welded structures. Further increase in specific power of the equipment manufactured by the Plant required that ESW of increased-strength steels be used for the fabrication of welded-forged structures [5]. Cr–Ni–Mo steels were found to have low operational strength, which showed up in hot solidification cracking of the weld and HAZ metal [6, 7]. To solve the problem of increasing the operational strength under the ESW conditions, the cooperating parties conducted comprehensive research, which resulted in identifying of the factors affecting the sensitivity to crack formation and development of the measures to prevent cracking (new welding consumables, weldability evaluation method, special techniques to provide favourable thermal cycles and decrease welding stresses were developed and applied) [8–11].

Mastering of welding of increased-strength steels and improvement of the ESW technology made it possible to design and manufacture presses, hammers and rolling mills characterised by high performance. First of all, these were presses with a force of 300 and 500 MN, no-anvil hammers with a shock energy of 1.5 MJ, unique press with a force of 650 MN (made and supplied in 1977 to France [12]), rolling mills 2000 and 3600. The ESW equipment and technology available by that time made it possible to manufacture parts with electroslag welded joints, the annual output of such parts in the 1970s–1980s amounted to 10,000–12,000 t.

As part of the task of further improvement of the ESW equipment and technology, the Plant decided to build a new installation for ESW of heavy sections to meet the current production requirements, by equipping it with the process automation and monitoring means. For this installation the Institute developed the system for a guaranteed feed of electrode wires, and designed and manufactured the automatic welding device ASh-110 fitted with new power supplies (transformers A-481E). This equipment was assembled using a gantry unit, which was manufactured by the Plant particularly for that purpose. The new unique installation allowed welding of parts with mating sections of up to 5000 $\times$ 6000 mm (workpiece thickness $\times$ weld length). The installation provided a guaranteed quality of welded joints as a result of improving consistency of the electroslag process through automatic duplication of electrode wires fed to the welding zone [13].

Confirmation of the experience and potential of NKMZ was that in 2003 it was ordered to manufacture (based on joint engineering with «SMS Eumuco GmbH WAGNER BANNING», Germany) presses

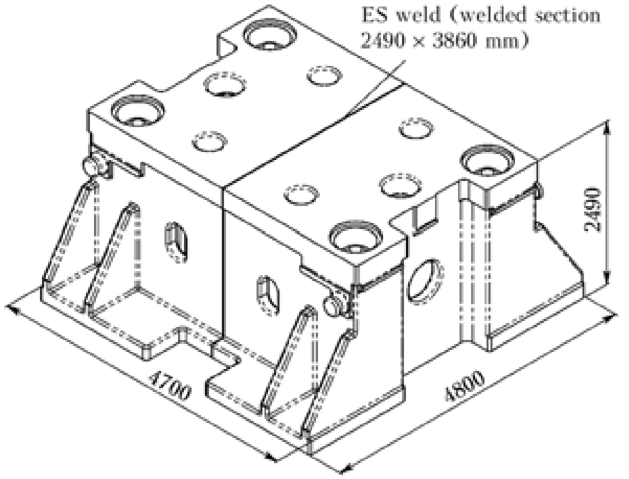

Figure 1. Schematic of lower spreader beam

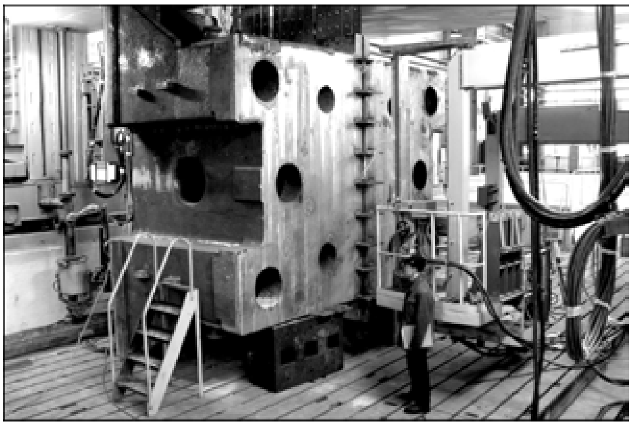

Figure 2. General view of the lower spreader beam in new installation for ESW of heavy sections

SPR-R5000 (50 MN), SPR-K5000 (50 MN) and SPR-R9000 (90 MN) to equip the wheel-rolling line for the Open Joint Stock Company MNTK (Nizhny Tagil, Russia). Part of basic components of the above presses (cylinder bottoms, spreader beams and distance pieces) was made welded by the consumable-nozzle ESW method. Cylinder bottoms were welded of two forgings of steel 20KhNMFA, according to TU 240013.030--87, using welding wire of the Sv-08GNMA type with a diameter of 3 mm, according to TU 14-15-375--95. Mating sections of the two types of the bottoms, depending upon the design of the cylinders, were 1730 × 2380 and 1430 × 2940 mm in size. The ES welded bottoms, each 100 t in weight, were subjected to postweld heat treatment (normalising and tempering). The lower spreader (Figures 1 and 2) 150 t in weight was welded of two cast billets of steel GS-20Mn5, according to DIN 17182, and then heat treated (normalising and tempering). The section

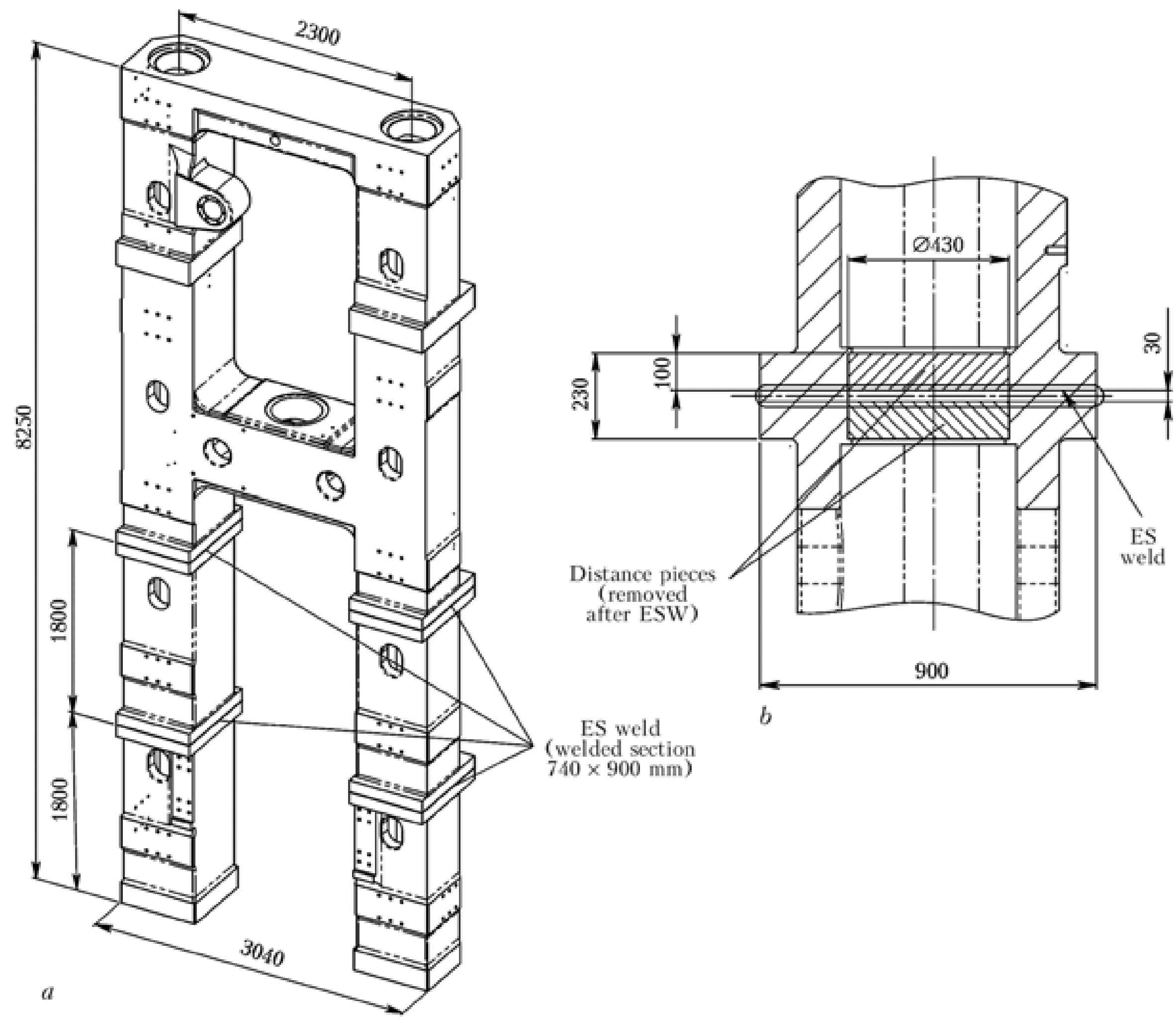

Figure 3. Schematic of the ES welded distance piece (*a*) and welded joint cross section (*b*)

welded was 2490 × 3860 mm in size. The appropriate technological measures were taken for ESW of 60 t distance pieces of cast billets of steel GS-20Mn5 (also using wire Sv-08G1NMA) to ensure the required accuracy and quality. Mating sections of the distance pieces were 740 × 900 and 880 × 1070 mm in size. To reduce the cycle and labour consumption in the manufacture of distance pieces consisting of five elements, they were assembled and ES welded in pack of two pieces in two stages (Figures 3 and 4).

Considering that large metallurgical enterprises of CIS, Europe and other world regions are now reconstructing their metallurgical and other facilities and building the new ones, NKMZ is active in the market of the corresponding products, winning priority orders for manufacture and delivery of different types of equipment and spare parts. Among other things, this is also favoured by many years of its cooperation with PWI in the field of ESW.

The immediate plans for cooperation between NKMZ and PWI include improvement of the ESW technology for making large bands (including in assembly site), which cannot be transported in their finished form, by the method of portioned counteraction to shrinkage forces to ensure the required accuracy of geometric dimensions of the bands after ESW [14]. This work also provides for building a system of mobile compact equipment for ESW and local heat treatment.

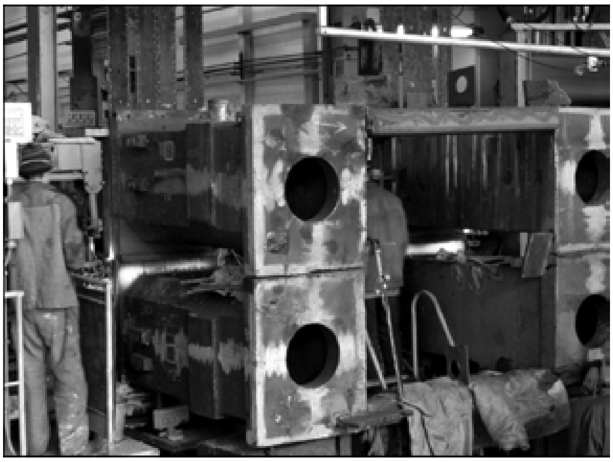

Figure 4. General view of the distance piece pack made by using ESW (two joints are made simultaneously)

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