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Advanced Studies and Developments of the E.O. Paton Electric Welding Institute in Welding and Allied Technologies

Abstract: The article presents a number of recent solutions developed at the E.O. Paton Electric Welding Institute including technologies and equipment for welding performed using highly-concentrated power sources such as plasma, laser and the electron beam. The above-named technologies were developed in order to weld pipes, thick titanium, aluminium–lithium alloys and high-strength steels. The solutions presented in the article also include vapour-phase technologies used in the production of nanostructured materials enabling the joining of composite materials and intermetallics. The article also discusses newly developed technologies and equipment used in underwater welding and cutting as well as a new electron beam tool for welding in outer space. In addition, the article suggests the application of postweld treatment based on high-density electric impulses and high-frequency mechanical peening in order to increase the service life and reliability of welds. In addition, the article presents the use of digital equipment based on high-sensitive solid-body converters used in non-destructive tests of welded joints as well as the application of industrial robots provided with a technical vision system in relation to products characterised by complex geometry. The article also presents a new method enabling the growing of single crystals of refractory metals and new equipment enabling the welding of live tissues.

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

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Fusion welding, pressure welding and allied technologies have enjoyed a stable and continuous development. In developed countries, more than a half of the GDP is generated by industrial sectors utilising welding processes. Welding processes are widely used not only in industry and civil engineering, but also in the production of household equipment, sports equipment and objects of artistic value as well as in medicine. Welding technologies are indispensable

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in industrial applications, improve our living standards and greatly contribute to the development of modern societies.

The analysis of trends observed in relation to the global welding engineering market justifies the conclusion that welding technologies will continue to be extensively used in various industries with the growing demand for energy-saving welding processes utilising highly concentrated sources of energy (plasma, laser electron beam) or hybrid solutions. Automation and robotisation will increasingly and continuously dominate welding processes. In turn, welding processes themselves will find applications in areas providing the most effective use of welding methods and technologies. The implementation of new structural solutions will enable improvements in welded structures. The weight of welded structures will continuously decrease as a result of using high-strength steels and alloys. However, the aforesaid weight reduction should not be at the expense of the service life and quality of welded structures. Because of the foregoing, in the recent years the Electric Welding Institute in Kiev has carried out very important R&D taking into consideration developmental trends in areas and directions of welding science and technique.

As a highly concentrated energy source, plasma has become increasingly popular in welding processes and allied technologies. The Electric Welding Institute has successfully developed a number of solutions. The improvement of technological and economic parameters when joining thick-walled materials was possible due to the development of a technology enabling the fast plasma welding of 12 mm thick alloys in one run. In addition, the Institute has developed a plasma welding torch of unique design, a plasma module and a control system including a programmable logic controller (PLC) connectable with a welding robot. The above-named devices enable operation involving the use of current impulses of selected waveforms, with the stepped and stepless wide-range adjustment of impulse and inter-impulse pause duration as well as the operation involving the use of direct current as well as straight and reversed polarity pulsed current. If compared to welds obtained using the TIG method, the weld made using plasma welding is characterised by a 40% narrower width, lower filler metal consumption as well as by the more fine-grained and homogenous structure of the fusion zone. In addition, linear energy is between 2.5 and 3 times lower, whereas the hardened zone is 1.5 smaller.

A significant achievement of recent years has been the development of a hybrid plasma-arc welding method [1, 2]. The combination of two sources powering welding arc has led to the obtainment of greater base material penetration depth. The technology enabling the welding of steels and aluminium alloys having thicknesses restricted within the range of 5 mm to 12 mm has made it possible to increase the welding rate by 25÷40% and reduce the consumption of the filler metal by 40% in comparison with that characteristic of pulsed GMAW. The implementation of the above-named technology necessitated the development of a new plasma torch (Fig. 1) and primary technological processes.

High physico-chemical properties of welded joins made in aluminium alloys can be obtained using the spot plasma welding technology (and

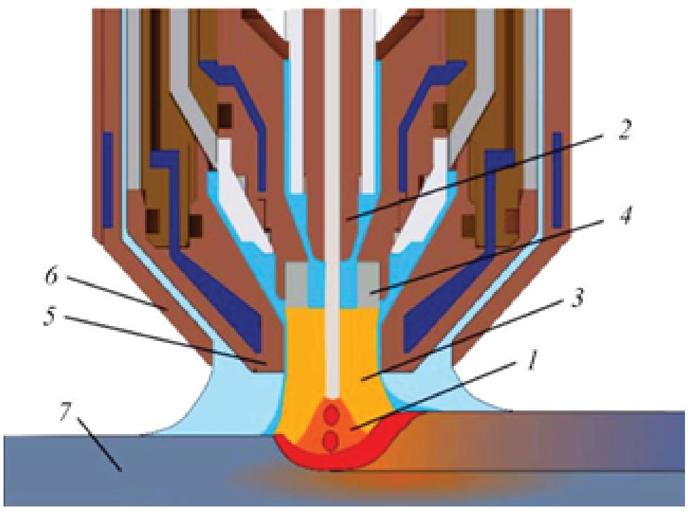

Fig. 1. Schematic diagram of the hybrid plasma torch: 1 – consumable electrode wire; 2 – consumable electrode contact tube; 3 – narrowed plasma arc; 4 – tubular electrode of the plasma torch; 5 – plasma jet; 6 – shielding gas jest; 7 – workpiece

dedicated equipment), utilising appropriately shaped impulses and stabilised arc length. In comparison with the spot resistance welding technology, the spot plasma welding technology can be used in cases of one-sided access to a welding area. The cathodic cleaning of surfaces of welded aluminium alloys combined with high efficiency and lower energy consumption enable the implementation of the above-named technology in robotic welding lines.

The Institute has also developed a process enabling the high-performance supersonic plasma spraying with metallic powders as well as powdered alloys, ceramics and their mixtures. The implementation of the technology required the development of new-generation devices featuring the separate feeding of components of inexpensive air-based plasma gas with a 5÷10% addition of methane or propane. By generating a supersonic jet, the plasma torch increases the kinetic energy of deposited particles by between 9 and 16 times, improving all operating properties of coatings. Adhesion increases by between 1.5 to 2.0 times in comparison with that characteristic of coatings formed through plasma spraying involving the use of below-supersonic parameters.

The Institute carries out research on laser and electron beam applications. Based on state-of-the-art disc and diode lasers, the Institute has developed a technology and automated equipment enabling the laser welding of high-strength steels, stainless steels as well as aluminium and titanium alloys.

In Ukrainian and overseas plants, the Institute has carried out industrial research on laser welding of dissimilar materials, stringer type panels, RRD nozzles, aerospace tankers, thin-walled containers and housings as well as other components of aviation equipment.

The Electric Welding Institute is one of the leading developers and manufacturers of electron beam welding equipment exported to many countries all over the world. Depending on the chamber size, electron beam welding devices developed and manufactured at the Institute can be divided into several type, i.e. small (0.26÷5.7 m^3), medium (19÷42 m^3) and large (80÷100 m^3) (Fig. 2). Depending on customer's needs, a specific type of a chamber is selected and an appropriate technology is developed [3]. Chambers are usually equipped with mechanical fixtures and an electron gun, the movements of which are controlled by a precise multiaxial mechanism. The mechanism is controlled numerically, providing the full control of electron gun movements along three axes and rotation restricted within the range of 0° to 90° in the z-x plane (from the vertical to the horizontal position). The rotation of an element is ensured by precise welding positioners rotating in the horizontal and vertical plane. The highest technological flexibility is provided by a welding positioner with an inclined axis of rotation, making it possible, among other things, to weld complex coaxial sections of aero-engines or components of variable shapes.

Fig. 2. Typical chamber for electron beam welding provided with a moving electron gun and a moving welding positioner

Depending on intended applications, the chamber can be equipped with a high-voltage inverter power source (15, 30 or 60 kW) and the RASTR system of secondary-emission electron visualisation, presenting the view of the welding zone before, during and after the welding process.

The Institute can rely on its extensive experience of developing electron devices and technologies intended for applications in outer space. The Institute has carried out works aimed to develop a new generation of electron beam welding equipment usable in outer space both during fixing and repair works (Fig. 3).

Fig. 3. Manual electron gun with a high-voltage connector

The Institute has always paid particular attention to the manufacturing and welding of pipes. Over the past years, the Institute has developed and tested technologies and equipment for the making of non-rotary joints of pipes having a thickness of up to 10 mm and a diameter of up to 200 mm made of high-strength steels. The welding process used when making the above-named joints involved the use of magnetically controlled arc. In physical terms, in the above-named process, arc affected by an external magnetic field (generated by appropriate magnetic systems) moves along the gap between edges of pipes being joined. A welded joint is formed as a result of pressure exerted by the pipes and plastic strains of pipe edges. A factor decisive for the formation of a stable joint is the presence of a liquid metal layer at the initial stage of exerted pressure.

Underwater welding is one of research and development areas, where the Institute's research workers have achieved significant scientific and technical results, e.g. in the development of welding consumables. Theoretical and experimental tests concerned with the burning of arc under water and ensuring the stability of arc welding processes performed under various hydrostatic pressure conditions enabled the development of new flux-cored wires for the wet welding of low-carbon steels and high-strength steels [4].

The underwater arc cutting of steels and alloys performed at a depth of up to 200 m required the development of appropriate covered electrodes, flux-cored wire and a new semiautomatic device, the feeding mechanism of which is located under water in the direct vicinity of a diver-welder [5]. Tests concerning the mechanical properties of the weld metal demonstrated the high quality of works performed using the underwater welding technology. The welded structures have been characterised by decades-long reliable operation. The comparison of fatigue test results concerning welded joints subjected to cyclic loads revealed that the properties of the joints were not inferior to those of the joints made under normal conditions (Fig. 4).

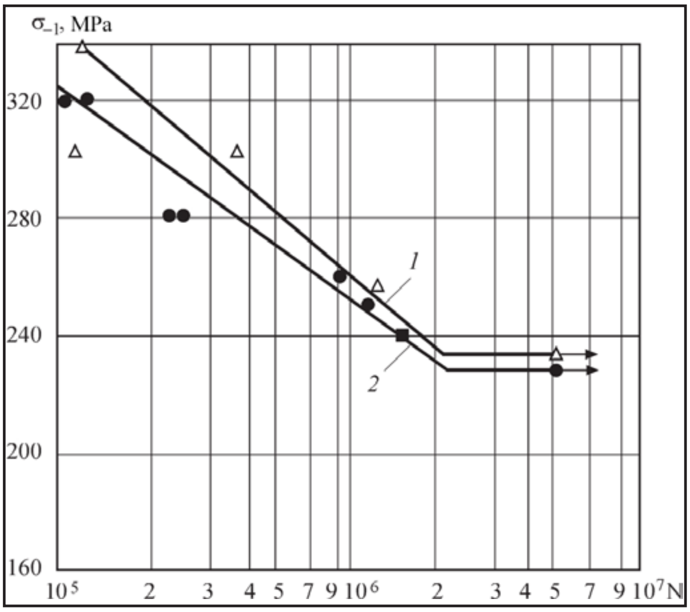

Fig. 4. Fatigue strength: 1 – underwater welding; 2 – welding in atmospheric conditions

Titanium is one of the principal structural materials used in many industries today, particularly when making crucial structures. Since the development of a technology for the welding of thin titanium sheets, i.e. the early 1950s, the Institute has continuously and extensively addressed issues related to the welding of titanium and succeeded in developing a technology enabling the narrow-gap TIG welding of medium and large-sized elements made of titanium. The technology is characterised by the low consumption of a filler metal wire, the possibility of obtaining narrow welds and heat affected zones (HAZ), reduced angular strains and slight internal welding stresses. To ensure the melting of the weld metal with the side walls of the weld groove it was necessary to apply a controllable variable magnetic field. The Institute has developed a UD 682 machine for the welding and surfacing of joints having a thickness of up to 110 mm and a length of up to 4 m (Fig. 5). The UD 682 device was used to make welded joints of titanium alloys PTZV (ПТ3В), VT6 (ВТ6) and VT20 (ВТ20) of various thicknesses. Related tests confirmed the high quality of the welded joins. The strength of the welded joints made of titanium VT6 and filler metal SPT2 (СПТ2) constituted 95% of the base material strength. In turn, toughness KCU of the weld metal amounted to 85 J/cm². The content of gases in the weld metal was similar to that in the filler metal wire, which demonstrated the high quality of the shielding gas.

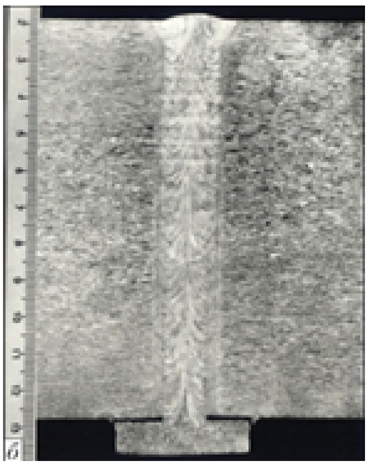

Fig. 5. Macrostructure of the welded joint made of titanium

Titanium alloys are widely used in the making of aviation and aerospace structures. The Institute has performed a number of tests aimed to develop a technology enabling the distortion-free welding of stringer type panels made of higher strength titanium (VT20) without compromising high accuracy and strength under cyclic load conditions. It was demonstrated that the making of slot welds using the TIG method on the activating flux layer using the initial plastic strain and the higher-frequency mechanical treatment of welds increased the service life of the above-named panels in comparison with those made using electron beam welding and submerged arc TIG welding. The application of the pre-weld plastic strain of sheets and stiffening ribs, the value of which was restricted within the range of 0.3 to 0.4 Re eliminated welding strains and provided necessary conditions for performing automated welding processes. It was determined the welded joints of the above-named panels could be effectively tested (NDT) using electron shearography.

One of important characteristics related to structural materials used in aerospace technique and equipment is appropriate specific strength. Aluminium-lithium alloys of various chemical compositions are characterised by low density and high specific strength. However, the lack of knowledge related to the welding of such alloys prevented their applications in welded structures. The Institute has performed a number of tests focused on the weldability of aluminium-lithium alloys. The results obtained in the tests enabled the development of effective welding methods and the making of a modified filler metal wire with a scandium addition. The research works also involved tests concerning the effect of the welding methods on the strength and the cracking susceptibility of various zones of joints made in aluminium-lithium alloys (Fig. 6).

To solve issues related to geometric and technological adaptation during the robotic welding of crucial structures, the Institute has

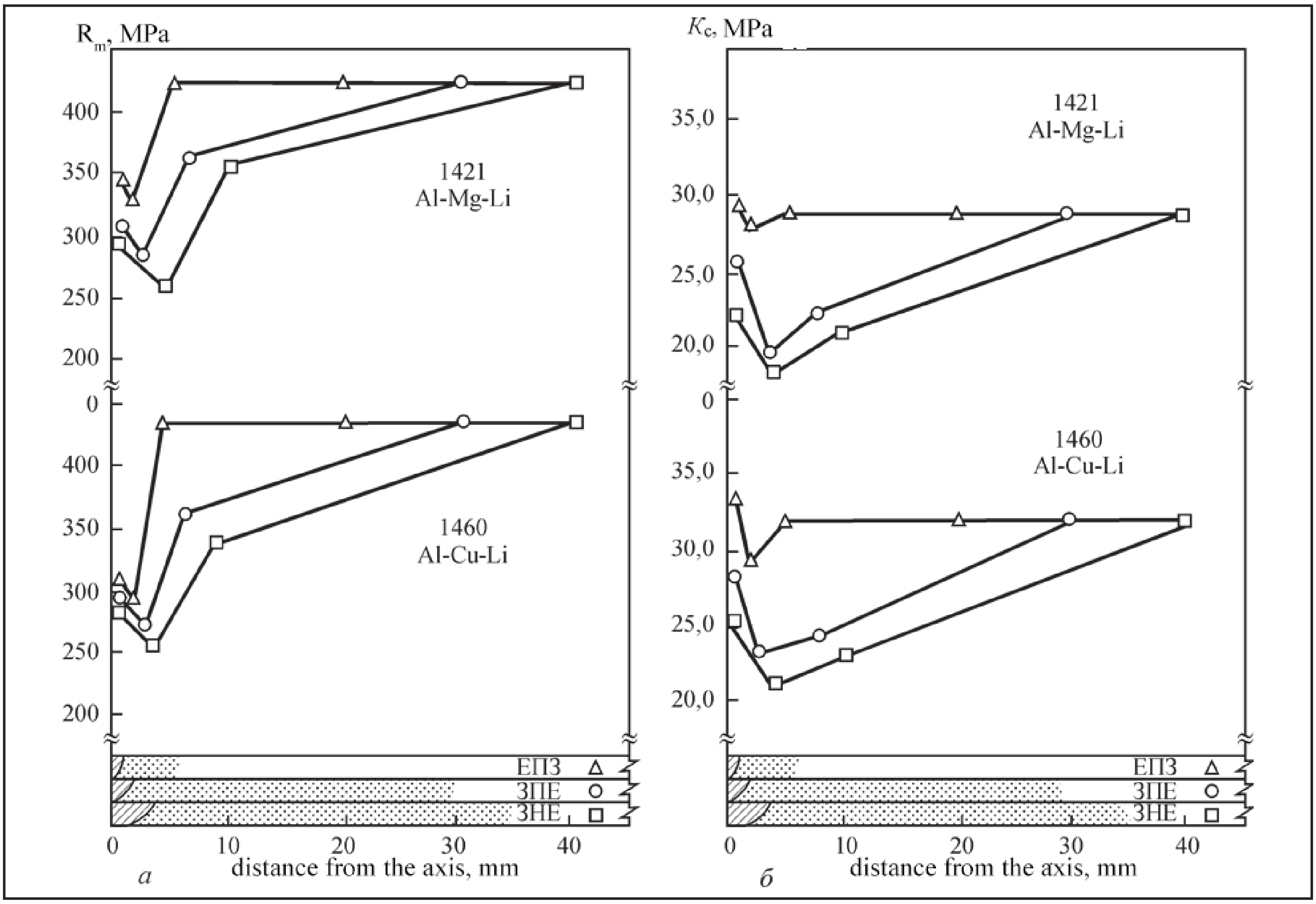

Fig. 6. Effect of electron beam welding (EBW), gas metal arc welding (GMAW) and TIG welding (TIG) on the strength Rm (a) and cracking resistance Kc (b) of various zones in joints made of aluminium-lithium alloys 1421 and 1460

developed special tracking systems. Welding robots provided with tracking systems automatically locate the interface as well as correct movement trajectory and welding parameters on a real-time basis. As a result, it is possible to compensate for matching and tacking inaccuracy and perform fully automatic welding operations. The tracking systems developed at the Institute are successfully used with robotic stations manufactured by Abb, Fanuc or Kuka.

Because of their unique properties, composites and intermetallic materials are increasingly often used in various industrial sectors, civil engineering, medicine etc. Regrettably, their use is restricted by the lack of reliable technologies enabling the making of joints in structures composed of dissimilar or nanostructured materials. The use of traditional welding and brazing methods cannot provide the appropriate service life of composite and intermetallic materials.

To address the above-presented issues, the Institute has developed a technology enabling the obtainment of nanostructured materials in the vapour state with the significant length of grain boundaries, which, in terms of their chemical composition, are similar to base materials [6, 7]. Figure 7 presents structures of some nanomaterials based on one-phase and heterophase systems. Nanostructured materials are characterised by high plasticity during heating and low alloy diffusive mobility activation energy. If used as an intermediate layer (in the form of foils), the above-named nanomaterials (Fig. 7a) solve problems accompanying the welding of intermetallic alloys and composites [8, 9]. Figure 7 also presents the structures of joints made of the γ-Ti–Al intermetallic material-based alloy (Fig. 7b) and of the nickel-based high-temperature creep resisting alloy (Fig. 7c). The high reactivity of intermediate foils and their superplasticity during heating in external

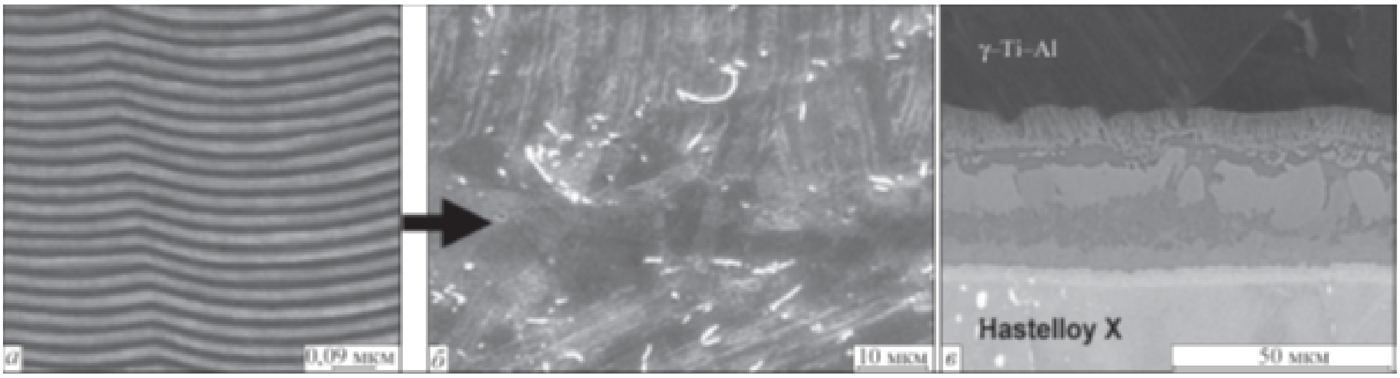

Fig. 7. Structure of the nanolayered foil and welded joints obtained using nanostructured materials: a) microstructure of the cross-section of the nanolayered foil composed of titanium (dark) and aluminium (bright) layers; b) microstructure of the γ-Ti–Al-based alloy joint.; c) microstructure of the γ-Ti–Al-based alloy joint with the nickel-based high-temperature creep resisting alloy

load conditions enable the performance of reactive brazing processes within a short time, during which a joint area is subjected to heating combined with low pressure. This technological sequence can be used when performing repair works performed when heating a joint area and, at the same time, being confronted with restricted access to welding power sources and limited applicability of intense radiation beams, e.g. in outer space.

Presently, structures are fabricated using numerous technologically advanced materials, yet steel remains the primary structural material. The Institute has carried out many tests aimed to identify optimum welding conditions in relation to high-strength steel 10G2FB (10Г2ФБ) with microagents of vanadium and niobium as well as steel 12GN2MFAJ (12ГН2МФАЮ) and 12GN3MFAJDR (12ГНЗМФАЮДР) [10, 11]. It was ascertained that the likelihood of cold crack formation in welded joints made of high-strength steels could be considerably reduced by applying a welding technology providing the cooling of joints at rate $w_{6/5}$ not exceeding 10°C/s, the content of diffusive hydrogen in the weld deposit not exceeding 4 cm^3/100g and the level of internal stresses in the joints amounting to less than 0.5 of the yield point. The above-presented tests enabled the development of reliable and effective technologies making it possible to weld low-carbon alloy steels having a yield point of 1000 MPa and higher. The aforesaid technologies were used when making steel structures of the roof of the "Olympic" stadium in Kiev, high-capacity containers for storing oil and other objects.

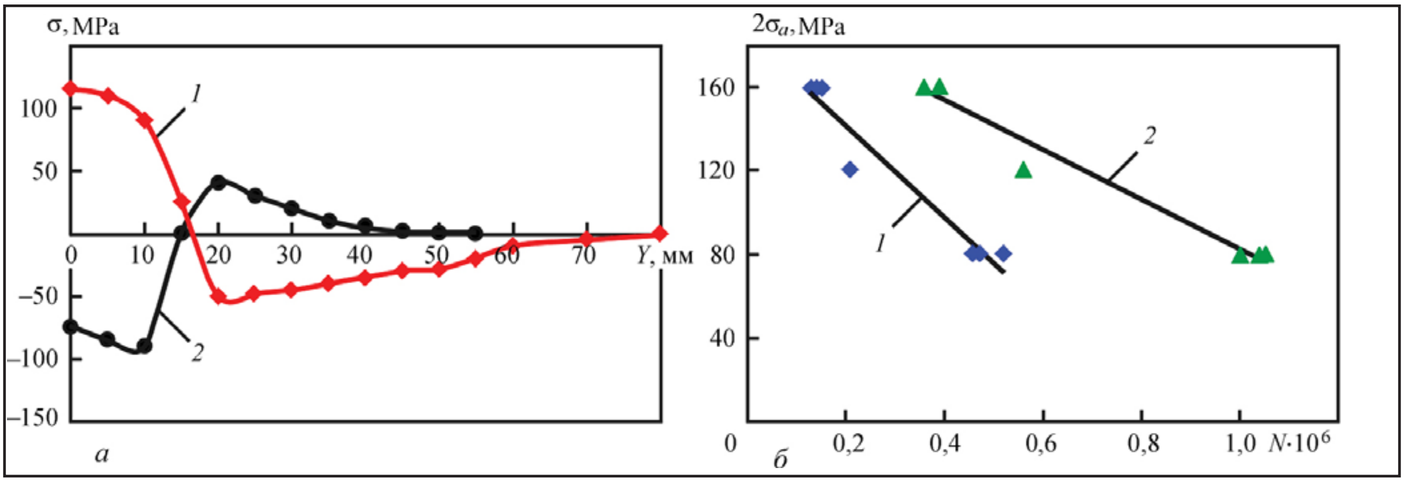

Fig. 8. Effect of electrodynamic treatment on the internal stresses and service life of the TIG welded joints made of alloy AMg6: a) internal stresses in the joints not subjected to treatment (1) and in the joints subjected to treatment (2); b) results of the fatigue tests of the welded joints not subjected to treatment (1) and in the joints subjected to treatment (2)

Reliability is one of the most important features characterising welded structures. The Institute has developed numerous technological processes to provide the aforesaid reliability. The processes developed by the Institute include electrodynamic treatment (EDT) and higher frequency peening mechanical treatment (HFPMT). Based on high-density current impulses, the electrodynamic treatment increases ductility, refines the structure of metals, significantly reduces internal stresses (Fig. 8a) and increases the fatigue strength (Fig. 8b) of welded joints. The devices developed at the Institute enable the removal of internal welding stresses generated during the grooving of thin-walled structural materials. The technology and equipment enabled the treatment of crucial joints of ship hull and aircraft structures, extending their service life [12, 13]. The tests performed at the Institute demonstrated that the use of high-frequency peening mechanical treatment decreased the intensity of corrosion and fatigue-triggered damage to steel structures [14÷16]. The effect of ambient industrial atmosphere in a temperate climate was modelled by placing specimens of T-joints and butt joints made of steel 15HSND (15ХСНД) (350 mm × 70 mm × 12 mm) in a climatic test chamber and testing the former for 1200 hours at a temperature of 40°C and a humidity of 98%. Fatigue tests of the specimens were performed under conditions of variable tension (exerted at a frequency of 5 Hz). The test results revealed that the ultimate 2 million cycle-based fatigue strength of the T-joints and butt joints increased by 47% and 39% respectively, whereas the cyclic fatigue strength of the welded joints increased (depending on a load) by up to 7 times.

One of important areas of the Institute's research activities is the development of reliable and efficient technologies and equipment increasing resistance to conventional wear, used, among other things, in metallurgy, power engineering, in the production of agricultural machinery etc. The complex research concerning the effect of surfacing technological parameters on the formation of the structure and changes in the physico-mechanical properties of overlay welds in relation to a carbon content in steels used in rolling stock wheels (restricted within the range of 0.55% to 0.75%) resulted in the development of a new arc surfacing technology for repairing freight car wheelsets [17]. The use of the above-named technology increased the toughness of the HAZ metal and the brittle crack resistance of overlay welds by 2-3 times. The service life of railway rolling stock wheels has been extended more than by twice.

The Institute's research works focused on brazing and started in the early 1960s have greatly contributed to the development of brazing technologies. The scientific fundamentals of the vacuum brazing of thin-walled structures made of various stainless steels have been used in the fabrication of crucial elements such as panels, aerials etc. Presently, the knowledge of physico-chemical processes occurring during the high-temperature vacuum brazing of high-temperature creep resisting dispersion hardened nickel alloys and principles governing the formation of the brazed joint structure enabled the development of the Ni–Pd–Cr–1Ge type brazing metal. The use of germanium as a depressant was dictated by the fact that germanium enables the obtainment of palladium-based solid-state structure in brazes. Brazed joints are characterised by stable strength restricted within the range of 1230 MPa to 1290 MPa at ambient temperature and between 1000 MPa and 1030 MPa at a temperature of 550°C, i.e. almost by twice higher if compared with industrial brazing metals. The developed brazing metal is used when producing centrifugal jet engine turbine wheels made of dispersion hardened nickel alloy (Fig. 9) and in the manufacturing of other products.

The successful development of welding technologies and reliable long-lasting crucial designs/structures would be impossible without quality control performed using non-destructive tests of welded joints.

Fig. 9. Centrifugal jet engine turbine wheel made using a new brazing metal

A significant achievement of the recent years has been the development of a portable X-ray and video device based on high-sensitivity state-of-the-art converters (Fig. 10). The portability of a relatively inexpensive device combined with the numerical processing of images enable the performance of radiographic tests of various objects under field and workshop conditions, in situations currently precluding the performance of "regular" non-destructive tests. The use of a portable X-ray and video device helps solve problems when inspecting the quality of many small-diameter gas, oil and water pipelines located at one site as well as of process pipelines in systems used for the chemical processing of crude oil and gas.

The automation and robotisation of non-destructive tests facilitate the defectiveness-related decision-making and eliminate the human factor. The Institute has developed a unit composed of an industrial robot and a tracking system enabling the performance of non-destructive tests of elements having complicated shapes (Fig. 11). The *Kaskad*-named unit identifies the geometry of a given object by scanning it using sensors generating eddy currents (without human intervention). The unit identifies the location of an object using a special tracking system, automatically maintains a constant distance between sensors and the object, stabilises the travel rate of the eddy current converter on the surface of the object, generates reports on product defectiveness, identifying the coordinates of defects in space, and provides the high quality of tests.

Fig. 10. Portable numerical X-ray and video device fixed on an object subjected to tests

Fig. 11. Robot with a tracking system used in non-destructive tests of products characterised by complex geometry [18]

The Institute successfully continues research concerned with the development of special metallurgical processes enabling the obtainment of high quality steels. However, the potential of such processes is not solely limited to the above-named area. Special metallurgical processes can also be used to make large-sized monocrystals, impossible to obtain using traditional methods. The Institute has developed a new process making it possible to "farm" crystals of refractory metals and involving the use of two different electric heat sources, i.e. plasma arch and induction heating (Fig. 12) [19]. Plasma arc enables the melting of a burden material (bar) and the appropriate shaping of the monocrystal body, whereas induction heating protects a local metal pool against leaks and generates a necessary temperature field in the crystal (as the crystal grows at an elevated temperature restricted within the range of 0.5 to 0.6 T_t [20]). The foregoing results in the reduction of stresses and dislocation density (below 106 cm^{-2}) in a growing crystal, which, in turn, favours the formation of a superior monocrystalline structure. The heating of a monocrystal up to a specific temperature is one of the key elements of the technology (rated among high-level additive technologies [21]). The Institute has developed a station for the making of large-sized tungsten and molybdenum monocrystals having the form of plates (20 mm x 170 mm x 160 mm) (Fig. 13).

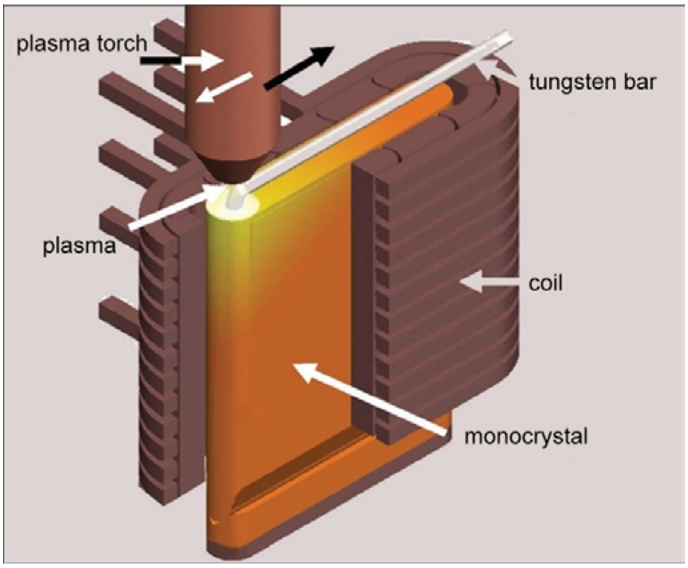

Fig. 12. Schematic diagram of fixtures used when making monocrystals of refractory metals

Fig. 13. Tungsten monocrystals

While welding remains to be one of the principal technological processes used when joining metals and other materials in various industries, it has entered an entirely new area, i.e. medicine. It is not much of an overstatement that surgeons' dream of the fast and bloodless separation and joining of live tissues without sutures has come true.

The Institute, in conjunction with Ukraine's leading medical institutions, has developed a technology and equipment (Fig. 14) for high-frequency current welding of live tissues [22÷26]. Presently, approximately 200 various surgical methods are used to perform between approximately 35 and 40 thousand procedures in abdominal and thoracic surgery, traumatology, pulmonology, proctology, urology, mammoplasty, ophthalmology, neurosurgery etc. New and continuously improved equipment for joining live tissues using high-frequency currents attracts interest from all over the world.

Fig. 14. EKV3-300 Patonmed device for welding live tissues

The Institute has continued its activity in medical applications and developed a new process of the non-contact convective-infrared treatment of live tissues. The process was thoroughly investigated and proved effective. It is used both in first aid interventions and during surgeries. The process enables arresting haemorrhages from parenchymal organs, small-diameter cancellous bones and small-diameter blood vessels as well as the curing of infected and hard-to-heal festering wounds, the coagulation of tissues to perform bloodless cutting and the performance of the thermal ablation of tumours and metastases. Each of the above-named technologies has its advantages and areas of application. The combination of the above-presented possibilities in one device significantly extends surgeons' intervention potential.

The above-presented overview of research activities performed by the Electric Welding Institute in Kiev demonstrates that principal works constitute the basis for the scientific development of new technologies and equipment. The Institute will continue to carry out future-oriented attractive research expected by the global welding engineering market.

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