International Scientific-Technical and Production Journal

The Paton WELDING JOURNAL

June
2012
 # 6

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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URL: www.rucont.ru

State Registration Certificate
KV 4790 of 09.01.2001

Subscriptions:
$324, 12 issues per year,
postage and packaging included.
Back issues available.

CONTENTS

SCIENTIFIC AND TECHNICAL

INDUSTRIAL

NEWS

DEPARTMENT FOR INVESTIGATIONS OF PHYSICAL-CHEMICAL PROCESSES IN THE WELDING ARC IS 50 YEARS

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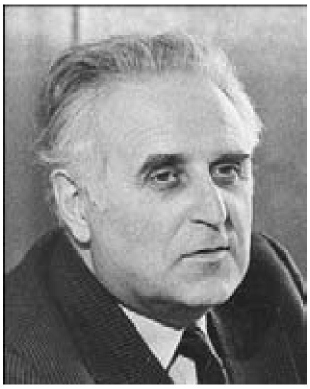

Rapid development of machine building, construction and other industries of the Soviet Union in the post-war years required elaboration and investigation of new consumables for welding of different grades of structural steels. Also, it was necessary to build new plants for industrial production of general- and special-application covered electrodes with improved sanitary-hygienic properties.

B.E. Paton made a decision to organise a new-level research into metallurgical and electrophysical problems of arc welding, as well as development of low-toxicity electrodes and technologies for their commercial manufacture. A new laboratory was arranged at the E.O. Paton Electric Welding Institute of the Ukr. SSR Academy of Sciences in 1958 to address these problems, the author of this article being appointed a head of this laboratory.

The laboratory completed a number of studies in the 1960s. An ingenious method for high-speed X-ray photography of fast processes was developed. The reliable data on the processes of melting and transfer of electrode metal in covered-electrode, underwater and submerged-arc welding were generated with the help of this method. The principles of kinetics of melting and transfer of electrode metal, distribution of temperature in the electrode metal drops, processes of heat exchange between the arc and molten metal at the electrode tip, processes of absorption of gases by the molten metal under the arc discharge conditions, as well as the patterns of distribution of hydrogen and nitrogen in the weld pool with the continuously moving interface between the liquid phase and solidifying metal were studied.

The mechanisms of the effect of welding parameters, density and polarity of the welding current on temperature of the drops, time of interaction of the drops with the environment, and type of a covering on the process of melting and transfer of electrode metal in covered-electrode welding were revealed. Relationship of the density and polarity of the welding current to temperature of the electrode metal drops, voltage gradient in the arc column and electrode metal transfer was determined.

Finding the principles of the processes of gas absorption and desorption allowed the new approaches to be used to interpretation of the mechanism of formation of porosity in the welds (I.K. Pokhodnya, A.M. Suptel, I.R. Yavdoshchin, G.G. Koritsky, A.P. Paltsevich, V.N. Gorpenyuk, B.A. Kostenko).

Results of these studies were presented in book «Gases in the Welds» by I.K. Pokhodnya, which was published in the USSR in 1972 and later re-published in the Czechoslovak Socialist Republic and in China. They served as a theoretical base for the development of many grades of advanced low-toxicity and high-efficiency welding electrodes characterised by favourable welding-operational properties, providing a dramatic reduction of harmful emissions and good mechanical properties of the weld metal. Coverings of the electrodes had original compositions, and were protected by author's certificates of the USSR and foreign patents.

To arrange mass, highly mechanised production of electrodes, it was necessary to design and build new high-capacity workshops. Short terms were allocated to accomplish this national economy task.

In 1962, the E.O. Paton Electric Welding Institute arranged the experimental production of welding electrodes, which made it possible to dramatically reduce the time from emergence of a scientific idea to its wide practical application (V.L. Borisyuk, L.F. Belozyorov).

In June 1962, the electrode laboratory was re-organised into the Department for Investigations of Physical-Chemical Processes in the Welding Arc, the efforts of which were highly esteemed both in the USSR and abroad.

A.E. Marchenko, I.R. Yavdoshchin and A.M. Bejnish conducted investigations at the E.O. Paton Elec-

Developers of mass-application low-toxicity electrodes (*from left to right*: I.K. Pokhodnya, A.E. Marchenko, I.R. Yavdoshchin)

tric Welding Institute on improvement of the electrode manufacturing technology. This work was completed in collaboration with GIPROMETIZ, «Promstalkonstrukstiya», Moscow and Kiev Institutes of the Occupational Hygiene and Professional Diseases, A.A. Baikov Institute of Metallurgy, as well as NIIMETIZ, TsNIITMASh, «Prometey», Moscow Electrode and Pilot Welding Plants, Magnitogorsk Hardware-Metallurgical Factory, Dnepropetrovsk Factory «Krasny Profintern» and Metalware Plant (later on called «Dneprometiz»), Odessa, Cherepovets and Oryol Steel Rolling Mills, Artyomovsky Plant «Pobeda Truda», Sulin Metallurgical Works, Gomel Starting Engine Plant and many others. The important national economy task, i.e. providing the country with the first-rate low-toxicity electrodes, was accomplished within the short terms owing to the joined efforts of welding scientists and metallurgists, designers and production workers.

Study «Radical Improvement of Labour Conditions and Rise of Productivity in Welding using Covered Electrodes and in Their Production» was awarded the State Prize of the USSR in 1971. Among the laureates were associates of the E.O. Paton Electric Welding Institute — I.K. Pokhodnya (leader), A.E. Marchenko, I.R. Yavdoshchin and A.M. Bejnish.

B.E. Paton suggested using flux-cored wire for erection works in order to mechanise welding. Production prototype of the flux-cored wire requiring no extra shielding of molten metal was developed in 1959 (I.K. Pokhodnya, A.M. Suptel).

I.K. Pokhodnya together with A.M. Suptel and V.N. Shlepakov studied peculiarities of heat and mass exchange and solid-phase interaction of components of the flux-cored wire core during heating, developed methods for regulation of the rates of melting of the wire sheath and core, and suggested methods for prevention of porosity in the welds. Kinetics of melting and transfer of the electrode metal was investigated, peculiarities of oxidation-reduction reactions of interaction between the metal, slag and gas phase were specified, and methods for controlling these processes were put forward, providing removal of the reaction products from the weld pool, optimal alloying of the metal matrix and high resistance of welded joints to initiation and propagation of cracks. A series of different-application self-shielding flux-cored wires characterised by original compositions and designs of the sheath was developed.

The development of self-shielding flux-cored wires was an advance in welding engineering and technology. Application of these wires allowed solving the problem of mechanisation of welding processes in erection works, in open shops, under field conditions and on the stocks. Lloyd Register of Shipping (Great Britain), Bureau Veritas (France), American Bureau of Shipping (USA), Germanischer Lloyd (Federal Republic of Germany) and USSR River and Sea Registers permitted the use of these wires for manufacture of critical hull structures of sea-going ships and river boats, thus increasing the productivity of welding. Flux-cored wires of a two-layer design were awarded the Gold Medal at Exhibition «Welding-75» in Brno (CzSR).

At the beginning of the 1950s, I.K. Pokhodnya suggested using flux-cored wire for CO_2 surfacing. I.K. Pokhodnya together with V.N. Shlepakov, S.A. Suprun, B.N. Golovko, Yu.A. Gavrilyuk, L.N. Orlov, G.A. Shevchenko, A.S. Kotelchuk, V.N. Upyr, A.A. Golyakevich and V.N. Ignatyuk developed a range of general- and special application gas-shielded flux-cored wires, which have been widely applied in industry up to now. This area that received a wide acceptance in the world welding science and technology is among the leading ones for raising the productivity of labour and improving the quality of the welded joints.

The flux-cored wire welding methods required development of special welding equipment, power sup-

Laureates of the State Prize of the USSR — developers of flux-cored wires (*from left to right*: I.I. Frumin, A.M. Suptel, I.K. Pokhodnya, V.N. Shlepakov, V.F. Alter)

plies and welding technology. Also, it was necessary to work out the high-productivity technology and equipment for manufacture of flux-cored wire, arrange mass production of this equipment, as well as design and arrange the highly mechanised production of the flux-cored wire. A.M. Suptel, V.N. Shlepakov, V.F. Alter, P.A. Kosenko, P.I. Rak and I.P. Kaplienko investigated technological peculiarities of manufacture of the flux-cored wire: combined plastic deformation of solid and granular materials, force conditions for their treatment, processes of shaping of complex-section composite materials, and continuous proportioning of multi-component powdered mixtures. These investigations were used as a base for the development of an advanced commercial technology for manufacture of flux-cored wires, designs of ingenious high-productivity devices for simultaneous shaping of a strip and proportioning of a powdered charge. Priority of our scientists in this field is protected by author's certificates of the USSR, Bulgaria and CzSR, as well as by patents of the USA, FRG, Great Britain, France, Italy, Austria, Switzerland, GDR, Hungarian People's Republic and other countries. The E.O. Paton Electric Welding Institute and Alma-Ata Heavy Machinery Plant built the high-productivity equipment for manufacture of flux-cored wires of various designs. Mass production of this equipment was organised.

Highly mechanised workshops for production of flux-cored wire were built in Ukraine and Russia. Domestic production lines, equipment and know-how were transferred to companies in the USA, FRG, France, Japan, CzSR, HPR, NRB, Argentina and China.

The authors' team consisting of I.K. Pokhodnya (leader), I.I. Frumin, A.M. Suptel, V.N. Shlepakov, V.F. Alter and associates of a number of other organisations were awarded in 1978 the State Prize of the USSR «For the Development, Arrangement of Mass Production and Application of New Materials (Flux-Cored Wires) for Mechanised Welding, Providing Rise in Labour Productivity and Improvement of Quality of Welded Structures».

The investigation results were summarised in books «Flux-Cored Wire Welding» and «Production of Flux-Cored Wire». The first of them was also published in CzSR.

In 1965, the efforts on development of methods and equipment for welding in space were started under the leadership of B.E. Paton. A.E. Marchenko, Yu.D. Morozov and V.I. Ponomarev, associates of the Department, took an active part in performing the comprehensive studies to investigate behaviour of molten metal in arc welding under the variable gravity conditions and peculiarities of the arc discharge between consumable electrodes in vacuum. An ingenious method for arc welding in vacuum and under zero gravity was developed. Testing of this method was included into the program of the world-first technological experiment — welding in space — which was conducted in 1969 by pilot-cosmonaut V.N. Kubasov on board the «Soyuz-6» spacecraft. The investigation results were published in books «Space Materials Science and Technologies» (1977) and «Space: Technologies, Materials, Structures» (2000).

Investigations of the key patterns of formation of the weld metal, alloying and solidification of the weld pool under conditions of artificial cooling of the weld surface and variable spatial position of the pool, which were performed by V.N. Shlepakov. V.N. Ignatyuk, Yu.A. Gavrilyuk, S.P. Giyuk and S.Yu. Yuzvenko, allowed the development of an advanced technology and equipment for position butt arc welding of pipes by using self-shielding flux-cored wire. The forced weld formation made it possible to raise the productivity of work from 3 to 6 times, compared to manual arc welding. The weld metal alloying systems and new flux-cored wires were developed. The optimal parameters of the welding process were specified to ensure high mechanical properties of the welded joints on pipes used to build main pipelines. The commercial technology was applied, and production of welding flux-cored wire for pipeline construction was mastered.

The E.O. Paton Electric Welding Institute, Design Bureau of the E.O. Paton Electric Welding Institute and Kakhovka Plant for Electric Welding Equipment built a specialised system of equipment «Styk» for position butt welding of 1220–1420 mm diameter pipes. The technology for automatic welding of pipelines by using the «Styk» systems was widely applied in construction of a number of main gas pipelines. The welding method, equipment and filler materials were covered by author's certificates of the USSR and patents of the USA, Canada, FRG, France, Japan, Great Britain and other countries.

In 1983, work «R&D Package on Development and Application of the Advanced Arc Welding Technology and Equipment (system «Styk») for Technical Re-equipment of Welding Production in Construction of Main Pipelines» was awarded the Prize of the Council of Ministers of the USSR. The team of authors comprised associates of the E.O. Paton Electric Welding Institute: I.K. Pokhodnya (leader), V.Ya. Dubovetsky, V.N. Shlepakov, A.N. Kutovoj, V.N. Golovko, V.A. Titarenko, P.A. Kosenko, V.A. Kotov and V.K. Sirik. In 1985 this work was awarded the Gold Medal at the Leipzig Fair.

In 1978, the Welding Electrode Plant belonging to the Ministry of Ferrous Metallurgy of the Ukr. SSR was affiliated to the E.O. Paton Electric Welding Institute. Within the short terms the Plant was reconstructed and fitted with new modern equipment. A new production of electrodes, flux-cored wires, welding fluxes and surfacing consumables was arranged there, and quality of the products was improved. Activity of the Pilot Plant for Welding Consumables, which was headed for over 33 years by P.A. Kosenko, favoured promotion of new developments of the Institute to the market. The team of the Plant works stably, upgrades production, is active in improvement of quality of the products, and maintains constant creative contacts with associates of the Department. The products of the Plant were highly recognised by production engineers and welders.

The experimental production of welding consumables at the Institute was re-arranged into the Scientific-Engineering Centre for welding and surfacing consumables. The head of the Centre is A.S. Bibikov, an associate of the Department. The Centre supplies experimental batches of welding consumables to industrial enterprises and construction companies of Ukraine and other CIS countries, which allows marketing the new developments of the Institute and arranging their production on an industrial scale. Association «Electrode» (P.I. Ignatchenko) helps much in this work.

The efforts on the development of advanced welding consumables, i.e. agglomerated fluxes for automatic welding, received further extension. D.M. Kushneryov, V.V. Golovko and S.D. Ustinov investigated metallurgical peculiarities of welding using ceramic fluxes and ways of decreasing the content of harmful impurities in the welds, and revealed the efficiency of modifying and microalloying of the deposited metal with these fluxes. These studies made it possible to develop new fluxes of the aluminate-rutile and aluminate-basic types, which are characterised by good operational properties and provide high mechanical characteristics of the weld metal. They were approved by the USSR Register of Shipping for fabrication of critical ship structures.

The efforts of the last decade were summarised by V.V. Golovko in his doctoral thesis «Interaction of Metal with Slag in Submerged-Arc Welding of Low-Alloy Steels Using Agglomerated Fluxes», which he successfully defended in 2006.

In the 1970s, the Department suggested using flux-cored wires for out-of-furnace treatment of metal melts. New types of wires containing highly reactive elements were developed for microalloying, modifying and desulphurisation of steels and cast irons. V.F. Alter, P.A. Kosenko, P.I. Rak and V.A. Savenko developed the technology and equipment for manufacture of large-diameter flux-cored wires. These efforts received further development at the I.N. Frantsevich Institute for Problems of Materials Science of the Ukr. SSR Academy of Sciences, Donetsk Scientific-Research Institute of Ferrous Metallurgy, Factory «Universalnoe Oborudovanie» (Universal Equipment) and other enterprises. At present the injection metallurgy method is widely applied at metallurgical works of Ukraine and Russia. Tens of millions of tons of steel melts were treated with this method.

The authors' team consisting of I.K. Pokhodnya, L.A. Poznyak, A.I. Trotsan and other scientists and production workers was awarded in 1999 the State Prize of Ukraine in the field of science and technology for elaboration of theoretical principles and wide application of the method for improving properties of structural steels by microalloying through flux-cored wires containing highly reactive elements.

The activity of the Department is characterised by the use of modern physical investigation methods, as well as mathematical modelling. X-ray fluorescent and diffraction analyses, scanning electron microscopy, X-ray spectral microanalysis, secondary-ion mass spectrometry, gas chromatography, high-speed X-ray and optical filming, multi-channel analysis of electric characteristics of the arc discharge and welding circuits are widely employed by the Department to study physical-chemical, metallurgical and electrophysical processes of arc welding. The methods of X-ray spectral analysis, scanning electron microscopy and secondary-ion mass spectrometry were used to investigate peculiarities of the mechanism of formation of strong adhesion of slag to metal during welding, and the ways were suggested for improving detachability of the slag crust (I.K. Pokhodnya, V.I. Karmanov, V.G. Ustinov, V.G. Vojtkevich).

New data were generated on distribution of elements in a welded joint, composition of non-metallic inclusions and liquation phenomena occurring in the welds.

A.E. Marchenko, N.V. Skorina and M.F. Gnatenko conducted rheological studies of multi-component

D. von Hofe, Managing Director of DVS, is introduced to the activities of the Department (1992)

systems of electrode coverings. Ways were proposed for intensification of manufacture and extrusion of covering mixtures, and improvement of reliability of the electrode manufacturing technology. New instruments for inspection of covering mixtures were developed.

Much consideration is given to improvement of the quality of welding consumables. Automatic analytical systems are developed for elemental analysis of electrode charges, flux-cored wires and agglomerated fluxes (V.I. Karmanov, V.G. Vojtkevich, V.V. Zagorodny, S.S. Ponomaryov, S.I. Seliverstenko).

New methods were suggested for analysis of diffusible hydrogen in the welds. These methods made it possible to substantially increase the accuracy of analysis and reduce the time to conduct it. They were standardised in the USSR and included into the USA and Japan national standards (A.P. Paltsevich).

V.G. Ustinov developed the procedure for quantitative evaluation of the content of nitrogen in iron–nitrogen, iron–nitrogen–titanium and iron–nitrogen–aluminium systems, allowing determination of nitrogen in solid solution and in nitride inclusions. The ingenious procedure for electron microscopic examinations of non-conducting materials was suggested. The mass spectrometry system with double focusing for investigation of molten metals, and system for mass spectrometry of thermionic emission of welding consumables were built.

The E.O. Paton Electric Welding Institute and the Institute of Nuclear Research of the Ukr. SSR Academy of Sciences developed the information-measurement systems for statistical analysis of electric and time parameters of the arc welding processes, investigation and testing of operational properties of welding consumables and power supplies (I.K. Pokhodnya, R.G. Ofengenden).

V.N. Gorpenyuk, S.S. Milichenko, V.E. Ponomaryov, L.V. Starodubtsev, V.I. Shvachko, I.R. Yavdoshchin and V.N. Shlepakov developed the high-productivity procedures for evaluation of stability of the AC arc and transfer of electrode metal. Implementation of these procedures in the information-measurement systems allowed reducing the time of processing of experimental data. The statistically reliable information was obtained on the effect of a kind, polarity and intensity of the current and composition of the electrode covering on stability of the AC arc and transfer of electrode metal.

The investigation results were summarised in book «Metallurgy of Arc Welding. Processes in the Arc and Melting of Electrodes», which was published in 1990. This book awarded with the Evgeny Paton Prize of the National Academy of Sciences of Ukraine (1996) was internationally recognised, translated into English and published in Cambridge (Great Britain).

The fundamental research into the mechanisms of evaporation of electrode metal, arc re-ignition, relationship of stability of the arc and character of electrode metal transfer with the electrode composition and welding parameters was used as a base for the development of low-toxicity versatile and high-productivity electrodes (I.R. Yavdoshchin, A.E. Marchenko, V.M. Bejnish, N.V. Skorina, V.N. Gorpenyuk, G.E. Kolyada, B.V. Yurlov, A.V. Bulat, G.G. Koritsky, A.A. Alekseev, S.S. Milichenko, A.S. Bibikov).

The new computerised systems were created, and the investigation procedures were upgraded (A.S. Kotelchuk, V.N. Shlepakov, L.A. Taraborkin, S.A. Suprun).

The Department extensively applies mathematical modelling of the arc welding processes.

In 1978, paper «Mathematical Modelling of Behaviour of Gases in the Welds» was presented by the author together with V.F. Demchenko and L.I. Demchenko at the Assembly of the International Institute of Welding. In 1979 this paper was published as a separate issue by the «Naukova Dumka» Publishing House. The Department performed investigations into peculiarities of growth of a gas bubble in the solidifying weld pool, interaction of molten slag with the solidified metal, thermodynamic properties of high-temperature processes occurring in the metal-gas-slag system, kinetic properties of interactions of slightly ionised plasma with molten metal, prediction of structure of the heat-affected zone of a welded joint, kinetics of solid-phase interaction of multi-component systems, etc. (V.I. Shvachko, L.A. Taraborkin, V.N. Shlepakov, A.S. Kotelchuk, I.I. Tsybulko, V.A. Pavlyk, O.V. Glushchenko, O.M. Portnov, A.V. Ignatenko). The investigation results are presented on a regular base at international seminars on mathematical modelling of welding phenomena «Numeric Analysis of Weldability», and at international seminars «Mathematical Modelling and Information Technologies in Welding and Related Processes».

The Department goes on looking for the efficient ways of improving sanitary-hygienic characteristics of welding consumables. Associates of the Department of the E.O. Paton Electric Welding Institute (V.G. Vojtkevich, I.R. Yavdoshchin, E.N. Onoprienko, V.I. Karmanov), Institute of the Occupational Hygiene and Professional Diseases of the Academy of Medical Sciences of Ukraine (Yu.I. Kundiev, I.T. Brakhnova, L.N. Gorban), Institute of Pharmacology and Toxicology, L.V. Pisarzhevsky Institute of Physical Chemistry and other research organisations completed a package of physical-chemical and biological investigations of the relationship between toxicity of fumes and composition of welding consumables. Investigations into the structure and phase composition of fumes by using a set of methods of electron and infrared spectroscopy, combined with determination of solubility of the particulate matter of welding fumes and their biological aggressiveness, allowed generating the data required for hygienic evaluation of welding consumables. The methods were developed for express assessment of toxicity of the welding fumes. They made it possible to obtain qualitative indicators of sanitary-hygienic properties of welding consumables and select those of them that have the minimum harmful impact on human organism. Results of investigations of the welding fumes were generalised in book «Welding Fumes» by V.G. Vojtkevich, which was published in 1995 in Great Britain, as well as in the paper by I.R. Yavdoshchin and I.K. Pokhodnya presented at International Scientific-Practical Conference «Protection of Environment in Welding Production» held in 2002 in Odessa. The data on the presence of quadrivalent manganese Mn^{4+} in fumes and dispersion of the welding fumes have been generated lately by using X-ray electron spectroscopy (I.R. Yavdoshchin, V.I. Karmanov, I.P. Gubenya).

Noteworthy are investigations into liquation of elements in the welds and formation of chemical microheterogeneity, conditions for rational alloying of the weld metal and role of some elements (nickel, manganese, silicon, phosphorus, copper, chromium and molybdenum) in formation of structure of the weld metal and variations in its cold resistance (I.R. Yavdoshchin, V.G. Vojtkevich, B.V. Yurlov, A.A. Alekseev, V.V. Golovko, V.N. Shlepakov, G.A. Shevchenko, L.N. Orlov, A.S. Kotelchuk, S.M. Naumejko).

The Department still gives much consideration to investigation of the problem of gases in the welds.

Results of these investigations were summarised in book «Metallurgy of Arc Welding. Interaction of Metal with Gases» published in 2004 by the «Naukova Dumka» Publishing House and awarded with the N.N. Dobrokhotov Prize of the National Academy of Sciences of Ukraine (I.K. Pokhodnya, I.R. Yavdoshchin, A.P. Paltsevich, V.I. Shvachko, A.S. Kotelchuk).

The latest scientific achievements in the allied fields: plasma physics, physics of metals, physics of strength, fracture mechanics, metals science, materials science, etc., are taken into account in development of new welding technologies and consumables. Investigations on the problem of hydrogen in welded joints can serve as an example.

Intensive emission of secondary negative ions of hydrogen was detected in investigation of iron samples saturated with hydrogen. This effect served as a base for the development of a new model of hydrogen embrittlement. According to this model, atomic hydrogen adsorbed on the surface of iron in the form of negative ions changes the energy state of a sub-microcrack, which initiates in the dislocation cluster during deformation and propagates in the initial period following the classic Griffith's scheme. The new model described the physical nature of the effect of hydrogen and allows the qualitative explanation of its known peculiarities.

The new concepts of the mechanism of the effect of hydrogen made it possible to develop the procedure for experimental investigation of sensitivity of steels to brittle fracture at the presence of hydrogen.

The new procedure allows evaluation of the effect of such factors as elemental composition and structure of metal, values of stresses, temperature, strain rate, and content and distribution of hydrogen in metal.

Results of comprehensive investigations of the mechanism of reversible hydrogen embrittlement of metals with the bcc lattice were generalised in the doctoral thesis of V.I. Shvachko and candidate theses of S.N. Stepanyuk and A.V. Ignatenko.

Studies of A.V. Ignatenko, V.S. Sinyuk and A.P. Paltsevich are dedicated to further investigations into reversible hydrogen embrittlement and mechanics of formation of hydrogen-induced cracks.

The mathematical model of transfer of hydrogen by edge dislocations was elaborated. The effect of hydrogen localisation of ductility on interaction of dislocations in iron was analysed. The physical model based on the dislocation theory was put forward to describe hydrogen embrittlement. The mathematical model of initiation and propagation of sub-microdefect in grain of the hydrogen-containing metal with the bcc lattice was worked out. Computer programs were

Associates of the Department in unofficial surroundings (2007)

developed, and computations were made to evaluate the effect of the complex stressed state of metal and hydrogen localisation of ductility. The temperature-rate dependence of the value of fracture stress was established. It was shown that, other conditions being equal, decrease in size of the metal grain leads to increase in the degree of hydrogen embrittlement. The stress-strain state of specimens with a stress raiser in three-point bending was computed allowing for microdefects. The presence of hydrogen in metal leads to formation of microdefects at a lower value of plastic strain. At a macrolevel, this leads to formation of a crack at smaller sagging of a specimen. The mathematical model describing kinetics of re-distribution of hydrogen in the welded joint allowing for energy traps was developed. The fields of concentration of hydrogen in the welded joints were investigated. Computations of the kinetics of removal of residual hydrogen are in good agreement with the hydrogen thermal desorption spectra obtained experimentally (A.V. Ignatenko, V.S. Sinyuk, A.P. Paltsevich).

The Department is active in investigations on controlling structure and properties of the weld metal by means of minor non-metallic inclusions (V.V. Golovko).

The effect of oxidation potential of welding consumables on the composition and structure of solid solution, quantity and composition of inclusions was studied. Inclusions 0.3–0.8 μm in size, consisting of titanium, aluminium and manganese oxides, favour increase in the content of acicular ferrite in structure of the welds. The mathematical model of formation of non-metallic inclusions in the weld metal was developed (L.A. Taraborkin, V.V. Golovko, S.N. Stepanyuk, D.Yu. Ermolenko).

The investigations of physical-chemical properties of powdered materials and mixtures simulating the flux-cored wire core, which were performed by using the methods of complex thermal analysis and mass spectroscopy of the gas phase in dynamic heating from 30 to 1500 °C, made it possible to reveal the temperature peculiarities of thermochemical reactions and evaluate the degree of their development and heat balance. Formation of melts at a stage of heating of the powdered core and evolution of gaseous products (H_2O, CO_2, SiF_4) determine the protective functions of electrode material and exert the substantial effect on the course of reactions of interaction of metal with gases at the drop and pool stages (V.N. Shlepakov, S.A. Suprun, A.S. Kotelchuk).

The new developments of the Department include:

- a range of versatile electrodes with good welding-operational properties, as well as ultra low-hydrogen electrodes for welding of high-strength low-alloy steels (I.R. Yavdoshchin, N.V. Skorina, P.A. Kosenko, A.E. Marchenko, A.P. Paltsevich, O.I. Folbort);
- advanced small-diameter versatile flux-cored wires (V.N. Shlepakov, P.A. Kosenko, Yu.A. Gavrilyuk, V.N. Ignatyuk, A.S. Kotelchuk, S.M. Naumejko);
- new agglomerated fluxes (V.V. Golovko);
- technology for manufacture of electrodes with two-layer covering (A.E. Marchenko);
- new low-toxicity electrodes produced by using combined lithium-containing liquid glasses (V.V. Skorina, M.O. Kiselyov, I.P. Gubenya).

A great contribution to the activities of the Department is made by associates of technical-engineering services (V.A. Savenko, V.S. Vlasenko, N.A. Varivoda, V.P. Pisarenko, Yu.V. Gobarev, N.K. Surmilo, I.G. Proskurin, Z.G. Kupriyanova, L.M. Skuratovskaya, D.Yu. Saranova). Their experience, knowledge and skill are highly esteemed by all the team of the Department.

During the entire time of existence of the Department much attention has been paid to selection of talented young people. Among associates of the Department are graduates of the Kiev Polytechnic Institute and Moscow Institute of Physics and Technology, Taras Shevchenko National University of Kiev, Kharkov V.N. Karazin National University, as well as Donetsk, Zaporozhie and Priazovsky Technical Universities.

The Department educated 38 candidates of sciences, six of whom became doctors of sciences. At present the Department has 3 doctors, 11 candidates of sciences and 15 engineers in its staff. Many of our colleagues became heads of enterprises, government employees, lecture at institutes of higher education and work at industrial enterprises. Some hold worthy positions at foreign research institutions.

The Department for Investigations of Physical-Chemical Processes in the Welding Arc closely collaborates with other departments of the E.O. Paton Electric Welding Institute headed by the prominent scientists: S.I.Kuchuk-Yatsenko, K.A. Yushchenko, V.I. Makhnenko, L.M. Lobanov, G.M. Grigorenko, I.V. Krivtsun, V.I. Kyrian and V.I. Galinich, as well as with the Institute for Problems of Materials Science, Institute for Superhard Materials, Physical-and-Technological Institute of Metals and Alloys, Institute of Ferrous Metallurgy, Physico-Mechanical Institute, R&D Corporation «Institute for Single Crystals», Kharkov Institute of Physics and Technology, Institute for Problems of Strength, Institute for Metal Physics and Institute for Nuclear Research of the NAS of Ukraine, National Technical University of Ukraine «Kiev Polytechnic Institute», Taras Shevchenko National University of Kiev, many institutes of higher education and research institutes of the USA, Germany, Austria, China, Slovakia, Poland, etc.

Since its foundation, the Department has been characterised by close contacts with manufacturers and customers of welding consumables both in our country and abroad. The advanced welding consumables and technologies developed by the Department up to now are applied at enterprises and construction sites of Ukraine, Russia, Belarus, other CIS and foreign countries. Participation in designing of equipment, workshops and factories for manufacture of welding consumables, in arrangement of production of new raw materials, holding of conferences, schools, symposia and consultations, development of forecasts in the field of welding consumables and proposals on improvement of their production — it is by far incomplete list of activities of the Department.

Areas of future studies. Steel will remain the main structural material in the first half of the 21st century. Development of the new types of high-strength low-alloy steels, including with super low content of carbon, heat-resistant steels, steels for structures operating at low climatic temperatures, steels for cryogenic engineering, and various-application high-alloy steels, will be given the priority growth rates.

Arc welding will continue to take the most important position among numerous methods of fusion welding. To develop new welding consumables it is necessary to optimise the weld metal alloying systems and find ways of reducing the content of hydrogen, nitrogen, sulphur, phosphorus and other harmful impurities in the weld metal.

Welding-operational properties of materials, methods for decreasing of porosity, prevention of cracks, improvement of penetration, weld shape and slag crust detachability, improvement of arc stability, reduction of spattering and emission of welding fumes will be improved.

Physical and mathematical modelling of the arc welding processes will receive further development. Computerised data and knowledge banks, as well as expert systems on different-application welding consumables will be created. Much attention should be paid to upgrading of the equipment and technology for manufacture of welding consumables, sourcing of raw materials of the consistent quality, automation of analytical control and technological supervision of production.

To accomplish these tasks, much in demand are highly qualified specialists with a deep knowledge of the theory of welding processes, physics and chemistry, as well as specialists in the information technologies. Solving these problems will favour development of manufacture of a new generation of welded structures and welding consumables.

TECHNOLOGICAL PECULIARITIES OF LASER WELDING OF MEDIUM-CARBON ALLOYED STEEL

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Technological peculiarities of 4.4 kW Nd:YAG laser welding of medium-carbon steel of the Fe–Cr–Mn–Si alloying system, 3.0 to 10.4 mm thick, in one pass with through penetration have been studied. Compared with argon-arc welding, the present welding method provides 6–12 times reduction of time of machine welding, 2.5–4.5 times decrease in power consumption and 12 times decrease in consumption of filler metal.

Keywords: *laser welding, medium-carbon alloyed steel, penetration, welded joint, hardness, efficiency*

A-TIG arc welding with through penetration without backing is successfully used for joining of steel of up to 6 mm thickness and multipass A-TIG + TIG welding with bevel edges is applied at higher steel thickness though filling the groove by filler material. However, argon-arc welding is a low efficiency process and characterizes by higher heat input in the metal.

Laser welding with deeper penetration [1] is proposed for widening a nomenclature of welded parts and increase a quality of their joining. Therefore, obtaining of new experimental data on evaluation of technological peculiarities of laser welding of alloyed steels is of the interest.

Peculiarities of formation of butt joints from $S = 3.0$, 6.0 and 10.4 mm thick medium-carbon steel of the Fe–Cr–Mn–Si alloying system (KhGS) using Nd:YAG laser DY 044 (Rofin Sinar, Germany) of up to 4.4 kW power including in combination with TIG welding were studied in the work. Lens with focal length $F = 300$ mm was used for irradiation focusing. Ar, He, CO_2, Ar + 17 % CO_2 + 1 % O_2 and N_2 were applied as shielding gas.

Single pass welding of alloyed steel of 3 mm thickness with $v_{\mathrm{w}} \geq 150$ m/h speed at $p/v_{\mathrm{w}} \leq 29$ W·h/m linear consumption of electricity and $q/v_{\mathrm{w}} \leq 105$ J/mm heat input (Table 1, Figure 1) was carried out using the laser of indicated power. Reduction of power of laser irradiation up to 3 kW (1.47 times) necessitates the 5 times reduction of welding speed and 3.4 times increase of p/v_{w} and q/v_{w}. Welding speed should be reduced up to 60 and 48 m/h, p/v_{w} and q/v_{w} are to be risen up to 73.3 and 91.6 W·h/m and to 264 and 330 J/mm, respectively, for through penetration of 6 mm thick steel at 4.4 kW laser power in atmosphere of various shielding gases (CO_2, Ar and Ar + 17 % CO_2 + 1 % O_2. $v_{\mathrm{w}} = 10.5$–12.5 m/h, $p/v_{\mathrm{w}} = 419$–352 W·h/m and $q/v_{\mathrm{w}} = 1509$–1207 J/mm were used for CO_2 welding with through penetration without baking of 10.4 mm thick steel. The values of the latter parameters are not character for laser welding. Extrapolation of experimental data indicates the possibility of through penetration of alloyed steel of 11.0–11.5 mm thickness at reduction of welding speed up to 6–8 m/h.

Machine DU-044 is appropriate for welding of 6–7 mm thick steel. Laser welding of alloyed steel of

Table 1. Possibility of laser through penetration of alloyed steel

Thickness of steel, mm	P, kW	Shielding gas	v_{w}, m/h	q/v_{w}, J/mm	Width, mm	
					Weld*	HAZ
3.0	3.0	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	30 30 30	360 360 360	3.0/2.5 2.6/2.8 2.5/3.0	– – –
3.0	4.4	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	150 150 150	105.6 105.6 105.5	1.1/1.3 1.1/1.3 1.4/1.1	0.4–0.6 0.4–0.5 0.4–0.6
6.0	4.4	CO_2 Ar Ar + 17 % CO_2 + 1 % O_2	60 48 48	264 330 330	2.8/1.0 3.6/3.3 4.1/3.7	0.3–0.4 0.4–0.8 0.5–0.7
10.4	4.4	CO_2	10.5 12.5	1267.2–1508.6	5.6/4.6	2.0–4.0

*Values of width from the face are given in the numerator and from the back side – in the denominator.

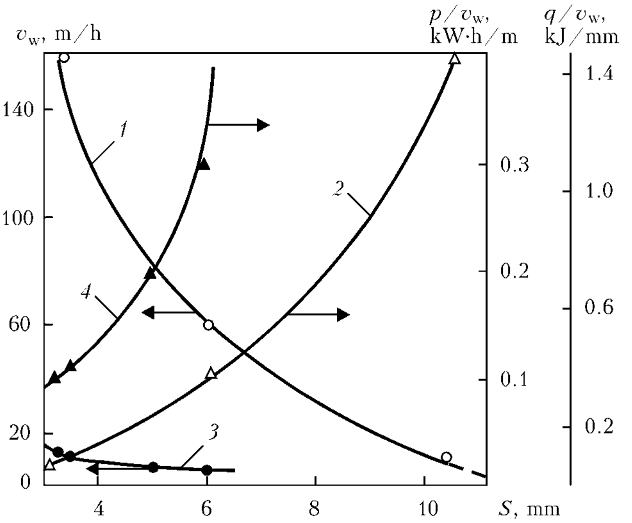

Figure 1. Comparison of welding speed, specific consumption of electricity p/v_w and heat input q/v_w in single pass welding using 4.4 kW power laser (*1*, *2*) and A-TIG method (*3*, *4*) depending on thickness of alloyed steel being welded

3–6 mm thickness is carried out with increased (8–12 times) speed, lower (3.5–4.5 times) consumption of electricity and metal heat saturation, reduced (4.5–7.5 times) consumption of shielding gas in comparison with A-TIG method. Speed of welding of 10.4 mm thick steel with square bevel increases approximately 2 times and number of passes reduces 3 times in comparison with argon-arc welding of the same steel with bevel edges, that result in 6 times reduction of time of machine welding. At that total consumption of shielding gas reduces 3–3.5 times and 2.5–3.5 times for electricity.

Welds made on 3.0, 6.0 and 10.4 mm thick steel using laser in one pass with through penetration have width 1.0–3.0, 1.5–3.5 and 3.5–6.0 mm, respectively. At that lager values refer to face of the weld (Figure 2). The narrower weld can be formed in the middle at 0.3–0.8 mm depth of steel thickness. The weld made on 10.4 mm thick steel can have sagging up to 2–3 mm and 1–2 mm deflection. Common increase of speed and power of laser irradiation is necessary for their reduction.

Additional welding passes with incomplete penetration and autoshaping of the welded joint are reasonable. Application of shielding gases including mixture with CO_2 promotes improvement of formation of penetration surface. Width of HAZ visually determined from the both sides of the joints of 3.0, 6.0 and 10.4 mm thick steel makes 0.2–0.5 and 1.5–3.0 mm and have inverse relation on speed of welding. Attached drops of molten metal take place on the surface of welded joints (Figure 3). Frequency of their location increases with rise of power density and energy of laser spot.

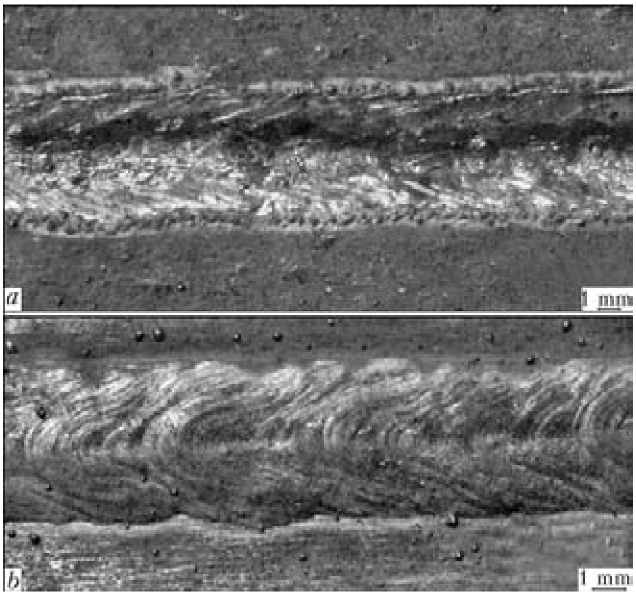

Figure 3. Appearance of surface of the butt joint from alloyed steel after laser welding without (*a*) and with (*b*) melting of filler wire

Incomplete laser penetrations of 10.4 mm thick steel have mushroom shape (Figure 4). Extrusion and displacement of the melt from under the laser beam to a tail and sides of the pool, rejection of liquid and solid particles, formation of narrow gas-metal channel of the depth equal to penetration depth take place under the effect of reactive pressure forming in the laser spot of metal vapor. Penetration beyond the bounds of gas-metal channel takes place through heating and melting with overheated melt and high temperature vapor-gas mixture.

Parameters of penetration depend on applied shielding gases (Ar, He, Ar + 17 % CO_2 + 1 % O_2, N_2 and CO_2). Ionized gas-metal flow (welding plume) is sufficiently transparent for laser irradiation of 1.06 μm wave length [2]. In this connection virtually similar depth of penetration (8.4–8.6 mm) takes place in application of such inert gases as argon and helium with ionization potentials U_i, differing 1.56 times,

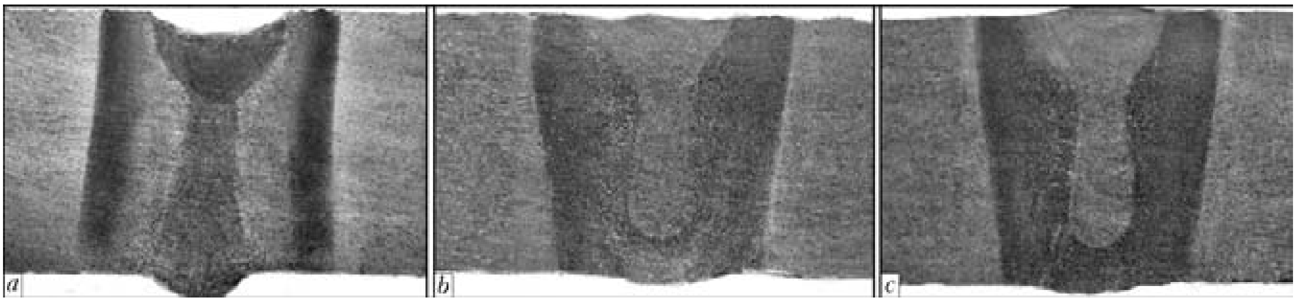

Figure 2. Cross section of butt joints from 10.4 mm thick steel of KhGS system with square bevel obtained using 4.4 kW power laser in one pass (*a*) and several (*b*, *c*) passes without (*a*, *b*) and with (*c*) melting of filler wire

Table 2. Chemical composition of metal after laser penetration of alloyed steel in different shielding gases

Shielding gas	C	Si	Mn	Cr
Ar	0.33–0.34/0.33	1.05–1.10/1.07	0.75–0.87/0.82	0.85–0.97/0.91
CO_2	0.33–0.34/0.33	1.02–1.10/1.05	0.71–0.77/0.74	0.81–0.90/0.87
Ar + 17 % CO_2 +1 % O_2	0.27–0.32/0.30	0.97–1.04/1.01	0.70–0.73/0.72	0.80–0.86/0.81
He	0.31–0.33/0.32	0.92–1.05/1.01	0.68–0.77/0.74	0.84–0.93/0.87
N_2	0.28–0.33/0.30	1.06–1.10/1.03	0.75–0.77/0.76	0.80–0.86/0.82

Notes. 1. Data on limits of value of chemical element weight fractions obtained after four analyses on height of penetration are given in the numerator and averaged values are in the denominator. 2. The base metal contains, wt.%: 0.33 C; 1.1 Si; 1.0 Mn; 0.98 Cr.

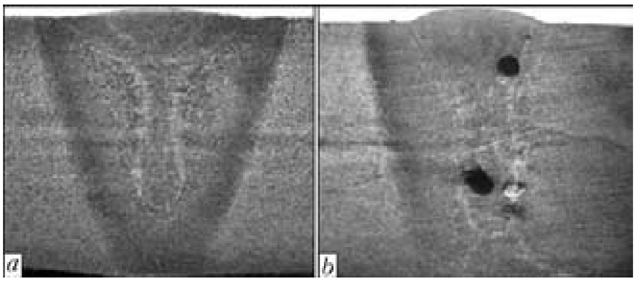

Figure 4. Incomplete laser penetrations in CO_2 (*a*) and argon (*b*) of 10.4 mm thick steel 30KhGSA

and which increases during application of CO_2 separately or in composition of Ar + 17 % CO_2 + 1 % O_2 mixture.

Laser welding of 30KhGSA steel in CO_2, Ar, He, Ar + 17 % CO_2 + 1 % O_2 and N_2 is accompanied by reduction of a content of carbon, silicon, chromium, manganese (Table 2) which remains (except for manganese) in the limits of requirements of GOST 4543–71, i.e. wt.%: 0.28–0.35 C; 0.9–1.2 Si; 0.8–1.1 Mn and Cr. Pores which are absent after welding in CO_2 and N_2 (see Figure 4) can be formed in the welds made with application of inert gases. CO_2 welding is recommended to be applied for alloyed steels.

Metal of the joint from alloyed steel welded by laser has higher hardness in comparison with the base metal. It increases from *HV*0.2-375 to *HV*0.2-450 with rise of v_w from 30 to 150 m/h at reduction of q/v_w from 360 to 106 J/mm (Figure 5) in the welds made on 3 mm thick steel. Reduction of metal hardness up to *HV*0.2-240–340/305 and *HV*0.2-230–280/265 after one and three passes is promoted by decrease of speed of welding and increase of its heat input in performance of the weld on 10.4 mm thick steel. There are no cold cracks appeared after laser welding of medium-carbon alloyed steel regardless increased hardness of metal of the joint.

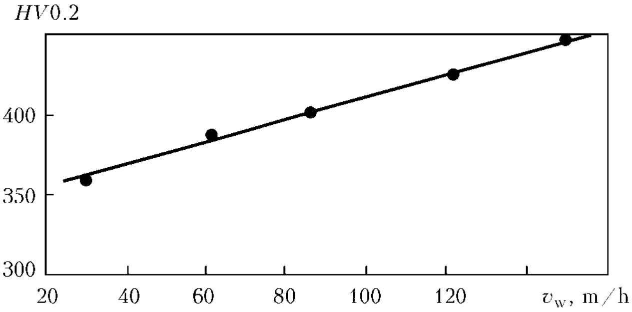

Figure 5. Dependence of metal hardness of weld made on steel 30KhGSA 3 mm thick on speed of laser welding

Vertical and double-sided laser welding are characterized by obtaining of quality butt joint from alloyed steel of increased thickness using higher speed. Width of the weld makes 5–6 mm (from the face), 2.5–3.0 mm (from the back) and 1.6–1.8 mm (Figure 6, *a*) at a depth of 2.0–2.1 mm in vertical welding of alloyed steel of 10.4 mm thickness at v_w = = 15.6 m/h. Shape and structure of the joint after double-sided welding remain, particularly, the same as in single-sided downhand welding. There are no need in using of welding wire and forming device for obtaining of the quality joint.

Double-sided 6 mm depth laser penetration of the joint with overlap of the layers can be realized with v_w = 48 m/h when q/v_w reduces up to 330 J/mm.

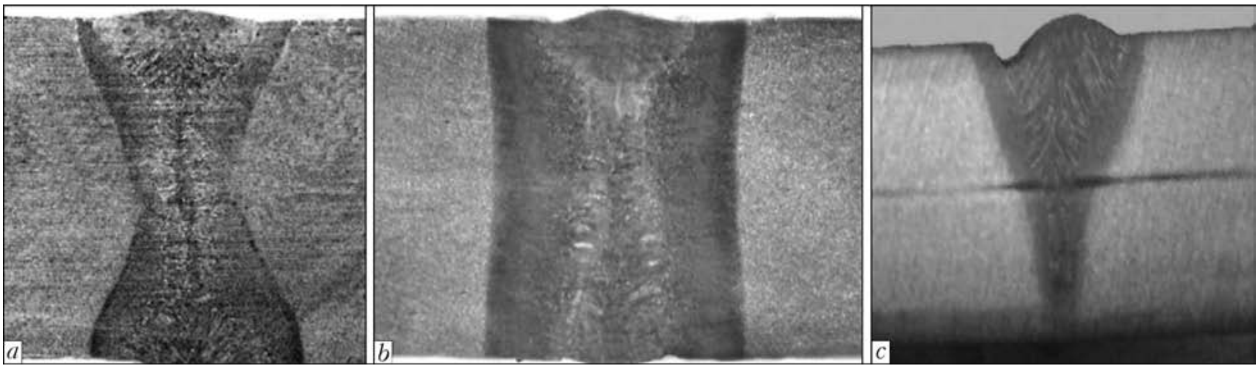

Figure 6. Macrosections of the joints from heat-strengthened steel (*a*, *b*) and steel without heat treatment (*c*) 10.4 mm thick obtained by laser vertical (*a*), double-sided (*b*) and hybrid (*c*) welding

At that time of machine welding, total consumption of electricity and shielding gas reduce 2–2.2 times in comparison with downhand welding. Absence of concavities, presence of small reinforcements and insignificant width of the weld (3.5 mm from both sides and 1.2–2.0 mm in the middle part), reduced width of visually identifying HAZ of thermostrengthened steel (from 0.5 to 1.2 mm near the surface up to 1.4–1.6 mm at a depth of 2–3 mm) (Figure 6, *b*) are character for the obtained joints.

Flat sample from alloyed steel in the as-welded condition with $\sigma_{0.2}$ = 830–850 MPa and σ_t = 940–970 MPa carries 34,900 cycles of tensile loading up to σ_l = 550 MPa and failures outside the joint in the place of transfer from working part to grip one.

It is well-known fact that the depth of penetration and speed of welding can be increased combining the laser beam and arc of consumable electrode [3]. Combining of two heat sources in one weld pool provides the greatest effect. Speed of hybrid welding with through penetration of 10.4 mm thick steel can make 35–40 m/h (Figure 6, *c*). Depth of penetration using these heat sources with the same parameters of welding equals 2.5–3.0 and 5.0–5.5 mm separately, i.e. in total less than 10 mm. Naturally, the through penetration of steel of higher thickness is possible at lower speed of hybrid welding.

CONCLUSIONS

1. It is determined that the butt joints of alloyed steel of up to 10.4 mm thickness can be performed in downhand position using though penetration of square bevel edges with 4.4 kW power laser.

2. Quality of the joint formation is improved through regulation of speed and rate of heat input, performance of additional passes and realization of double-sided and vertical welding.

3. 6–12 times reduction of time of machine welding, 2.5–4.5 times decrease of electricity consumption, 3–7.5 times decrease of shielding gas and 12–13 times reduction of filler wire consumption in comparison with tungsten electrode argon-arc welding are observed using laser irradiation of 4.4 kW power. Content of the main alloying elements and carbon remains at satisfactory level and manganese reduces by 18–28 %.

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INVESTIGATION OF STRUCTURAL TRANSFORMATIONS AND STRESS-STRAIN STATES OF PARTS OPERATING AT CYCLIC THERMOMECHANICAL LOADS AND ESTABLISHMENT OF FUNDAMENTALS FOR SURFACING PARTS WITH HIGH FATIGUE CHARACTERISTICS

Research work on this subject was finished in 2011 at the E.O. Paton Electric Welding Institute (Subject Manager – Prof. I.A. Ryabtsev)

Basing on the modern models of tough-plastic non-isothermal flow, thermokinetic diagrams of decay of austenite of deposited and base metal using a numerical method of finite elements, the method of calculation has been developed which makes it possible within the frame of only single model to calculate the stress-strain and structural state of parts at single- and multi-layer surfacing and their effect on fatigue life at cyclic thermomechanical loads after surfacing and in the process of service.

The new method has been developed and experimentally confirmed for improving the thermal strength of deposited parts due to surfacing of a sublayer of low-carbon low-alloy steel, which has a high ductility and fatigue strength. Calculation of stress-strain and structural state in the process of surfacing and service cyclic thermal loads of parts of mill rolls type, deposited by a tool steel without and with a ductile sublayer, showed that due to relaxation of stresses the surfacing with a ductile sublayer provides the reduction of stresses by 25–30 % in the most loaded external working layer, thus resulting in 30–35 % increase in thermal strength of the deposited part. Calculations were confirmed by experimental investigations of thermal and mechanical fatigue life of the deposited parts.

The investigation allowed us to develop the new surfacing materials and technologies of surfacing the parts which operate under conditions of wear and cyclic mechanical or thermomechanical loads: driven shaft-gears and geared rim of autogenous mill; steel rolls of pipe rolling mills TPA 30-102 and sheet-rolling mills; dies, parts of crane MKT-250, etc.

ASSESSMENT OF HYDROGEN INFLUENCE ON DELAYED FRACTURE OF WELDED JOINTS FROM HIGH-STRENGTH LOW-ALLOYED STEELS

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Hydrogen influence on delayed fracture of welded joints of high-strength low-alloyed steels was studied by the Implant method. A calculation model based on material creep theory was proposed for assessment of hydrogen contribution to delayed fracture process.

Keywords: *arc welding, welded joints, high-strength low-alloyed steels, delayed fracture, calculation model*

Welding of high-strength low-alloyed (HSLA) steels is accompanied by formation of cold cracks which appear at unfavourable combination of structural factors (intensive grain growth, high level of stresses and strains) and increased content of hydrogen [1]. The cause for cold crack initiation is hydrogen-induced cold cracking [2, 3]. Hydrogen influence is manifested in the delayed nature of fracture process [4, 5]. In this connection development of methods of adequate assessment of hydrogen influence on the process of welded joint fracture is urgent.

One of the methods for determination of delayed fracture susceptibility of welded joints is application of implant method, which combines certain features of direct and indirect methods of welded joint testing for cold cracking sensitivity.

The purpose of this work is development on the basis of creep theory of calculated model for assessment of hydrogen contribution into the process of delayed fracture of welded joints of HSLA steels.

Samples-inserts from 14Kh2GMR and T-1 steels (Table) of shape and dimensions as per GOST 26386–84 were tested. Deposition of a bead with sample-insert was performed with 4 mm ANP-2 electrodes in the following mode: $I_w = 170$ A; $U_a = 25$ V; $v_w = 10$ cm/min. Diffusible hydrogen content in the bead was determined by the glycerin method. Fracture stress in the weakened section σ_{fr} and time to fracture τ_{fr} were recorded. Test results (Figure 1) confirmed the leading role of diffusible hydrogen during delayed fracture of welded joints from low-alloyed steels that is in agreement with the data of work [6]. Delayed fracture susceptibility of samples-inserts made from the above steels turned out to be approximately the same (see Figure 1).

Mechanism of delayed fracture of steel welded joints is characterized by common features of material fracture at creep [2]. In [7] at consideration of crack propagation at stress relaxation as a particular case of fracture under creep conditions, a calculated model based on Yu.N. Rabotnov principle was proposed for assessment of material crack resistance.

In this work the conducted testing procedure allows controlling the force parameters, so that it is rational to replace the value of stress intensity factor (SIF) in [7] by force parameters. The following model was obtained:

$$\frac{\sigma_{fr}}{\sigma_t} = \frac{1}{1 + mq\tilde{\Gamma}(\tau)}, \qquad (1)$$

where

$$\tilde{\Gamma}(\tau) = \int_0^{\tau} \Gamma(\tau - S)dS; \quad m = \frac{1}{1 + p};$$

σ_t is the ultimate tensile strength; σ_{fr} is the stress at which the sample failed; q is the structural parameter related to SIF; $\Gamma(\tau - S)$ is the aftereffect kernel; $p = p([H])$ is the energy parameter of the system (sample) [7], in this case being a function dependent on hydrogen content.

Let us consider limit cases of model (1).

When the system is open, $p = p([H]) \to \infty$ ($m = 0$), i.e. hydrogen content is small enough and system fracture resistance is independent on hydrogen concentration. At hydrogen saturation, when

Composition (wt.%) of 14Kh2GMR and T-1 steels

Steel grade	C	Mn	Si	Cr	Ni	Mo	V	Ti	B	S	P
14Kh2GMR	0.12	1.12	0.32	1.35	0.08	0.38	0.01	0.045	0.0050	0.045	0.023
T-1	0.21	0.95	0.31	0.54	N/D	0.18	0.08	0.028	0.0035	0.017	0.010

$p = p([\mathrm{H}]) \to 0$ ($m = 1$), hydrogen influence is maximum, and system crack resistance also depends on structural parameter q ($0 < q < 1$ [7]). Therefore, parameter m of the proposed model (1) changes in the range of [0–1].

Results of calculations by formula (1) in comparison with experimental data are given in Figure 2. Calculations were conducted at different values of parameter p (q = const) and with the following kinds of integral operator kernel, describing the aftereffect [7]:

1) constant kernel (Maxwell body)

$$\Gamma(\tau - S) = \lambda, \qquad (2)$$

where λ is the material constant;

2) exponential kernel (standard linear Kelvin body)

$$\Gamma(\tau - S) = \lambda_1 e^{-\beta(\tau - S)}, \qquad (3)$$

where λ_1, β are the rheological constants;

3) power kernel

$$\Gamma(\tau - S) = \frac{\lambda}{(\tau - S)^{1-\beta}}, \qquad (4)$$

where $0 < \beta < 1$.

As is seen from these formulas, the first term in the sequence in exponential kernel expansion (3) and the power kernel (4) at $\beta \to 1$ give Maxwell body kernel.

Calculations by model (1) using the above aftereffect kernels showed that experimental data are described best of all by exponential kernel (3) of Kelvin body (Figure 2). Maxwell type kernel (2) leads to somewhat underestimated results at maximum hydrogen content, but at its moderate content, it satisfactorily describes the experimental data. Power kernel (4) gives an unsatisfactory description of the initial sections, but it can be used at longer-term testing (see Figure 2).

Analysis of calculation curves showed that there exists a possibility for assessment of the influence of hydrogen and structural factors on fracture, respectively, by m and q parameters. Limit of $\lim\limits_{\tau \to \infty} \frac{\sigma_{\mathrm{fr}}}{\sigma_{\mathrm{t}}}(\tau)$ function when exponential and power aftereffect kernels are used allows assessment of minimum value of fracture stress $\sigma_{\mathrm{fr.min}}$ at different hydrogen content. At maximum hydrogen content ($p = 0$) this value, when Kelvin body is used (3), is assessed to be on the level of $\sigma_{\mathrm{fr.min}} \approx 231$ MPa ($\sigma_{\mathrm{fr}}/\sigma_{\mathrm{t}} \approx 0.33$ at $\tau \to \infty$), and in the case when power aftereffect kernel is used (4) we have $\sigma_{\mathrm{fr.min}} = 210$ MPa ($\sigma_{\mathrm{fr}}/\sigma_{\mathrm{t}} = 0.3$ at $\tau \to \to \infty$). As estimates were obtained for the case with maximum possible hydrogen content in the sample, it is anticipated that at real hydrogen content minimum value of fracture stress is close to the experimental result (for 14Kh2GMP steel) $\sigma_{\mathrm{fr.min}} = 240$ MPa [2].

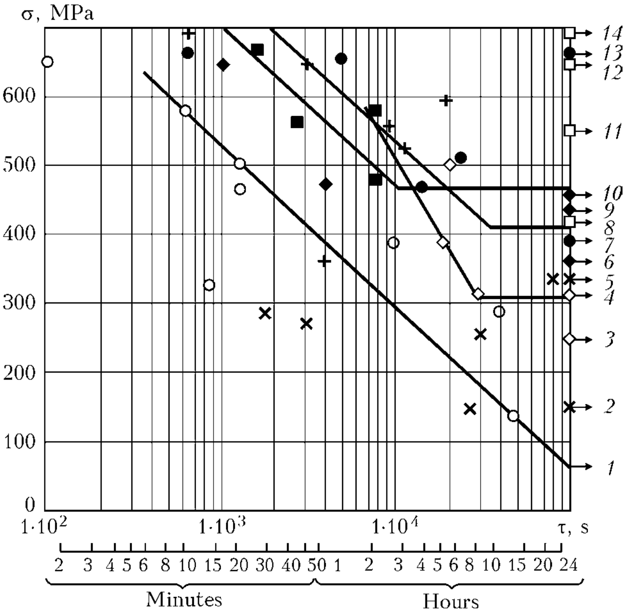

Figure 1. Experimental data on influence of diffusible hydrogen $[\mathrm{H}]_{\mathrm{dif}}$ on delayed fracture susceptibility of 14Kh2GMR steel samples-inserts (*1, 3, 4, 6, 7, 9, 11, 12, 14*) and T-1 (*2, 5, 8, 10, 13*): *1* — $[\mathrm{H}]_{\mathrm{dif}} = 14.8$ ($T_{\mathrm{av}} = -40$ °C); *2* — 15.0 (–25 °C); *3, 4* — 5.0 (–40 °C); *5* — 7.9 (20 °C); *6, 9* — 5.0 (20 °C); *7* — 7.9 (20 °C); *8, 10* — 5.0 (20 °C); *11, 12, 14* — 0.6 (–40 °C); *13* — 0.6 cm^3/100 g (20 °C)

Satisfactory description of experimental results by calculated curves allows assessment of the time to fracture, depending on hydrogen content. In the first approximation the simplest Maxwell kernel was used for qualitative assessment of hydrogen influence on time to fracture (2). Substituting (2) into (1), we obtain the time to fracture

$$\tau = (p + 1)\,\frac{1 - k}{k\lambda q}, \qquad (5)$$

where $k = \sigma_{\mathrm{fr}}/\sigma_{\mathrm{t}}$.

Based on analysis of empirical data, as well as allowing for exponential nature of thermoactivation dependence describing the energy interactions, parameter p was determined from the relationship

$$p([\mathrm{H}]) = \ln\left(1 + \frac{[\mathrm{H}]_{\max} - [\mathrm{H}]_0}{[\mathrm{H}]_0}\right), \qquad (6)$$

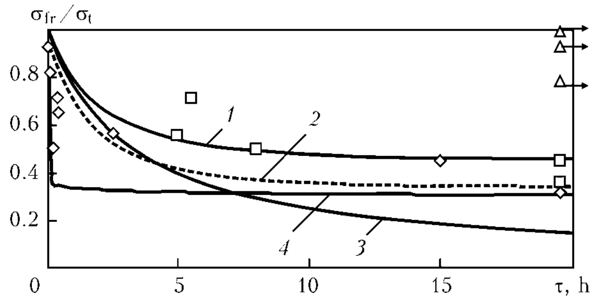

Figure 2. Calculated (curves *1–4*) and experimental data (symbols) with different aftereffect kernels: *1, 2* — aftereffect Kernel of Kelvin body at $[\mathrm{H}]_0 = 5$ and 15 ml/100 g in the sample, respectively; *3* — Maxwell body at $[\mathrm{H}]_0 = 5$ ml/100 g; *4* — power kernel at $[\mathrm{H}]_0 = 15$ ml/100 g

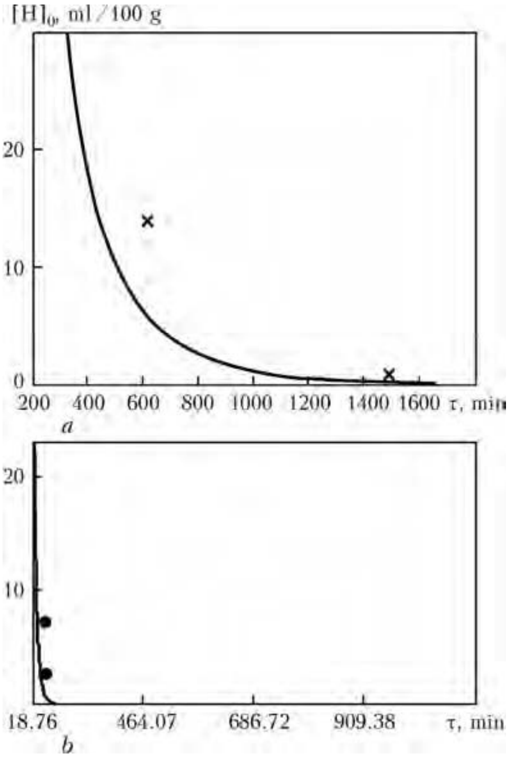

Figure 3. Influence of hydrogen content in samples on delayed fracture at loads σ_{fr} = 300 (×) and 650 (●) MPa (×, ● are experimental points)

where $[H]_{max}$ is the maximum hydrogen content (depends on steel grade and is determined empirically); $[H]_0$ is the hydrogen content in the sample, determined by the glycerin method.

Influence of hydrogen content on delayed fracture of the sample derived by formulas (5), (6) is shown in Figure 3. As is seen from the Figure, the shape of the curves does not change at different loads. However, at lowering of hydrogen content, the curve shifts towards longer time to fracture, that corresponds to increase of delayed fracture resistance of the samples. Results of calculation of the time to sample fracture depending on hydrogen content, based on simplest kernel of Maxwell body, lead to the assumption that when simpler kernels are used, it is possible to more accurately describe this process, but the qualitative picture here will not change. Thus, calculations conducted by the proposed model, showed that at lowering of hydrogen content delayed fracture resistance of welded joints increases. Calculation data are is good agreement with the experimental data.

The proposed experimental model can be used for assessment of hydrogen influence on the technological strength of welded joints of HSLA steels. Comparative simplicity of calculations by this model allows considerably simplifying investigation of the mechanisms of hydrogen-induced delayed fracture of welded joints.

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MECHANISM OF ELECTROMAGNETIC DEGASSING OF LIQUID METAL IN UNDERWATER WELDING

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A nonconvective mechanism of liquid melt degassing under the conditions of external electromagnetic impact in underwater welding is considered. It is established that the generated buoyancy electromagnetic force acting on gas bubbles and promoting their removal from the melt, is several times larger than the Archimedean force. By its magnitude and influence on weld pool degassing, it is comparable with the centrifugal force generated in the melt rotating under the impact of an external electromagnetic field.

Keywords: *underwater welding, weld pool, external electromagnetic impact, nonconvective degassing mechanism*

One of the possible ways to improve the quality of welded joints produced under the water is application of an external electromagnetic impact on the weld pool. This approach is quite well-established in welding in air [1]. However, because of the specific features of arc welding in aqueous environment, the above process needs to be adapted to these conditions. To determine the range of effective modes of external electromagnetic impact, a mathematical model was developed, which is based on magnetic hydrodynamics equations [2]. It takes into account the interaction of forces, which form in the liquid metal pool as a result of interaction of an external magnetic field and electric current of the arc proper. Obtained experimental data [3, 4] showed that at flux-cored wire underwater welding with external electromagnetic field intensity in the established range, hydrogen content in the deposited metal decreases 2.5 times, and the maximum pore size is reduced 5–15 times. As a result, strength properties of weld metal increase by 20, and its ductility (relative elongation) — by 40 %.

Mechanism of liquid melt degassing under the conditions of an external electromagnetic impact in underwater welding is described in [2]. In order to clarify the above phenomena, forces acting in welding on gas bubbles moving relative to the melt in the weld pool, including the Archimedean force, centrifugal force (in case of melt rotation), as well as Stokes force, are considered. It is determined that in the rotating melt with a radial distribution of current density degassing mechanism is purely convective, and the centrifugal force makes the same or greater contribution into degassing than does Archimedean force [2].

This work deals with the nonconvective mechanism of liquid melt degassing under the conditions of an external electromagnetic impact in underwater welding. In [5, 6] it is established that if a particle with different electrical conductivity is placed into liquid, then it will be moving at application of electric and magnetic fields.

In order to study the feasibility of a nonconvective mechanism of weld pool degassing in an external magnetic field, we have considered the impact of an electromagnetic buoyancy force on a spherical bubble [6–8]:

$$F_{\mathrm{b}} = \frac{3}{2}\, jBV\, \frac{\sigma_{\mathrm{p}} - \sigma}{2\sigma_{\mathrm{p}} + \sigma},$$

where j is the current density in the melt, A/m^2; B is the induction of external magnetic field, T; $V = 4\pi b_0^3/3$ is the volume of a bubble of radius b_0, m^3; σ_{p}, σ is the specific electric conductivity of pore (bubble) and melt, respectively, Ohm^{-1}/m.

If specific electric conductivity of a bubble is much smaller than the specific electric conductivity of the melt, then the absolute value of electromagnetic buoyancy force has the following form:

$$|F_{\mathrm{b}}| = \frac{3}{2}\, jBV.$$

Given below are the values of system physical parameters in SI system of units, used to consider the mechanism of melt degassing under the impact of the electromagnetic buoyancy force:

Welding current I_{w}, A	150–200
Vector of external magnetic field intensity $\vec{H}_0$, A/m	796–1592
Vector of induction of external magnetic field $\vec{B}_0$, mT	10–20
Melt temperature T_{m}, °C	$(2–3)\cdot 10^3$
Pool diameter d_{p}, m	$5\cdot 10^{-3}$
Dynamic viscosity of the melt η, Pa·s	$3.3\cdot 10^{-3}$
Melt density ρ, kg/m^3	7000
Kinematic viscosity of the melt $\nu = \eta/\rho$, m^2/s	$0.47\cdot 10^{-6}$
Estimated current density in the pool $\lvert\vec{j}\rvert = I/d^2$, A/m^2	$(6–8)\cdot 10^6$
Specific electric conductivity of the melt σ, Ohm^{-1}·m, at T = 2500 °C	$3.5\cdot 10^6$
Pool depth l, m	0.0025
Radius of bubbles (pores) in the mode of external magnetic field impact b, m	$4\cdot 10^{-6}$
Radius of bubbles (pores) without the influence of external magnetic field b_0, m	$12\cdot 10^{-6}$

Welding speed v_w, m/s 0.13
Surface tension of molten iron σ_0, mJ/m^2 .... $1.76\cdot10^3$

It is more convenient to write the previous formula in the form of

$$F_b = 2\pi jBb_0^3.$$

Let us assess the velocity of bubble removal v_b (i.e. melt degassing rate) under the impact of electromagnetic buoyancy force and compare it with calculated degassing rates under the impact of Archimedean force and centrifugal force (in a rotating melt) from [2]. For this purpose let us first equate the electromagnetic buoyancy force to Stockes force, which decelerates bubble removal:

$$2\pi jBb_0^3 = 6\pi\eta b_0 v_b,$$

whence

$$v_b = \frac{jBb_0^3}{3\eta}.$$

Thus, for nonconvective mechanism of weld degassing conclusions made in [2] for the convective mechanism are valid: rate of bubble removal is proportional to the square of their diameter.

Ratio of electromagnetic buoyancy force F_b to Archimedean force F_A acting on the bubble, can be expressed as

$$\frac{F_b}{F_A} = \frac{3jB}{2\rho g} \approx 2.5.$$

As a result, electromagnetic buoyancy force is approximately 2.5 times greater than the Archimedean force. According to the results of [2], the centrifugal force in the moving melt is almost two times greater than the Archimedean force, i.e. the electromagnetic buoyancy force has the same order of values and a comparable influence on melt degassing, as the centrifugal force. Therefore, at analysis of the number of bubbles in the melt, their spatial distribution and time of removal (floating) it is necessary to take into account the joint impact of electromagnetic buoyancy and centrifugal forces. Particularly important is the nonconvective mechanism of degassing, based on the impact of the electromagnetic buoyancy force on the bubbles, at application of an external magnetic field not along the normal to pool surface, but along the mentioned surface, when the circular melt rotation is absent.

There also exists a lower critical value of the magnetic field, after reaching which it has no impact on the degassing process. This critical field

$$B_{\min} = \frac{2\rho g}{3j} \cong 8 \quad [\mathrm{mT}]$$

corresponds to excess of the rate of bubble removal under the impact of electromagnetic buoyancy force over the rate of bubble floating under the impact of Archimedean force. Approximately the same value of the critical field (about 6 mT) was obtained also for the condition of excess of the rate of bubble removal under the impact of the centrifugal force over the rate of bubble floating under the Archimedean force impact in [2]. Lower value of external magnetic field can be also assessed proceeding from the assumption that it should be greater than the magnetic vortex field created by inductor current:

$$H_i = \frac{\mu_0 I}{2\pi d} \cong 6 \quad [\mathrm{mT}],$$

where μ_0 is the magnetic permeability of vacuum equal to $4\pi\cdot10^{-7}$ H/m.

All the three estimates made for the lower limit of magnetic field applied to improve weld quality, based on various physical criteria, give practically the same value of magnetic field intensity of about 6–8 mT.

The above-said leads to the conclusion that the electromagnetic buoyancy force is several times larger than the Archimedean force, and ensures the nonconvective mechanism of weld degassing at application of an external magnetic field in the weld pool plane with radial distribution of current density, when the pool convective rotation is absent.

If the external magnetic field is orthogonal to the pool surface with radial distribution of current density, the melt rotates as a whole around the external magnetic field direction, and then the nonconvective mechanism of melt degassing under the impact of the electromagnetic buoyancy force has the same order of values as the convective mechanism of degassing under the impact of the centrifugal force [2].

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MODIFICATION BY BORON OF DEPOSITED METAL OF WHITE CAST IRON TYPE

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The paper considers the effect of minor additions of boron on properties of hypoeutectic composition deposited metal of the white cast iron type provided by wide-layer hardfacing using flux-cored wire. It has been established that boron in an amount of 0.07–0.14 wt.% leads to a substantial improvement of crack resistance of metal of the deposited cast iron. It has been shown that growth of crack resistance is caused by modifying effect of boron on sizes and structural constituents of the deposited cast iron and strengthening of grain boundaries.

Keywords: *hardfacing, deposited cast iron, flux-cored wire, structure, boron modification and microalloying, crack resistance, hardness*

Formation of solidification and cold cracks in a deposited metal as well as in fusion zone is the main problem in hardfacing of parts manufactured from grey cast iron. Such defects can be a reason of fatigue failure in hardfacing of parts operating under cyclic and alternating loads (for example, crankshafts of car engines, compressors, diesel generators etc.).

Various methods of metallurgical and technological character, i.e. application of high-alloy surfacing materials of austenite class, pre-deposition of buffer sub-layer for reduction of carbon content in working deposited layer, preliminary and additional heating of deposited part and its delayed cooling after hardfacing etc. can be used for elimination of crack formation. However, such methods of crack elimination appear to be low-efficient or unacceptable for obtaining of thin layer of wear-resistant deposited metal over parts with relatively small (0.5–1.5 mm) wear-out which is characterized by a complex of difficult to combine properties (high hardness, wear and crack resistance).

Modification and microalloying by minor additions of surface-active elements (SAE) influencing the processes of structure formation of solidifying alloys [1] are one of the directions of improvement of physico-mechanical properties of iron-carbon alloys. Refining and strengthening effect of SAE on intergranular junctions (boundaries) which are a wide spread network penetrating the whole metal volume results in intergranular reinforcement of alloy matrix [2]. In turn the grain boundaries are energy barriers for crack propagation [3]. Thus, it can be assumed that SAE application can be an effective method for increase of crack resistance of alloys solidifying under non-equilibrium conditions of real welding process.

Boron refers to SAE and its peculiarity is a modimodifying capability, i.e. influence on grain size and condition of the grain boundaries [1, 2, 4, 5]. Boron alloying is also widely used in welding using flux-cored wires and strips for obtaining of abrasive-resistant deposited metal. In this situation it plays a role of a main alloying element taking part in formation of hard and wear-resistant carbides and carboborides of transition metals. Content of boron in such a type of deposited metal, as a rule, makes 1.5–3.5 wt.%. At the same time the information about the influence of relatively minor additions of boron on properties of low-alloyed cast iron deposited using flux-cored wire is not sufficient.

Aim of the present work was experimental study of effect of minor additions of boron on properties of deposited metal of the white cast iron type provided by wide-layer hardfacing using flux-cored wire of the parts manufactured from high strength cast iron with globular graphite. Composition of deposited metal developed at the E.O. Paton Electric Welding Institute and resistant under conditions of sliding friction at high contact loads [6], but solidifying at hardfacing with crack formation was taken as an object for investigation. Investigated deposited metal has the following chemical composition, wt.% : 2.4–2.6 C; 1.0–1.2 Si; 1.2–1.4 Mn; 0.5–0.6 Cr. Pilot flux-cored wires of 2 mm in diameter with different boron content were manufactured for obtaining and investigation of the samples of deposited metal with indicated chemical composition. Single wide-layer hardfacing of cylinder samples from cast iron with globular graphite was carried out at reversed polarity direct current using mode with 150–160 A current, 19–21 V voltage, 35 mm range of electrode oscillation, 5.5 m/h welding speed and 1.8–2.2 mm thickness of deposited layer.

Visual examination of the deposited samples showed that the macrocracks take place on the surface of deposited layer with no boron content and microcracks of various lengths and level of opening located in the deposited metal as well as in a fusion zone are present in the microsections. Nucleation of microcracks takes place, as a rule, in the fusion zone at the places of occurrence of graphite inclusions of the base metal and close to them areas of ledeburite colonies. Then they easily propagate in the whole volume of the deposited metal. At the same time, depos-

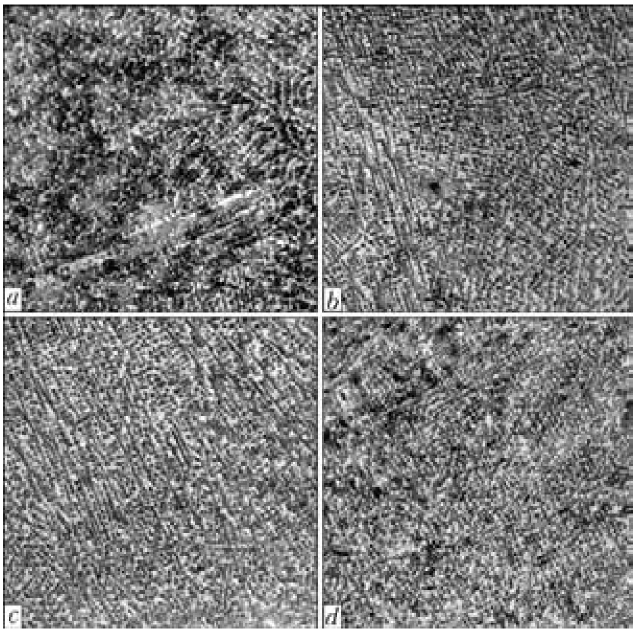

Figure 1. Microstructure (×80) of deposited metal with various content of boron: *a* — without boron; *b* — 0.07; *c* — 0.13; *d* — 0.21 wt.% B

ited metal with 0.05–0.07 wt.% B solidifies without formation of marcocracks and number of microcracks significantly decreases. Increase of boron content results in further reduction of amount of microcracks. Single microcracks take place at boron concentration 0.18–0.20 %. Boron microalloying of more than 0.2 wt.% makes not observable influence on crack resistance of the deposited metal. It was determined in a course of metallographic investigations that products of austenite decomposition (ferrite-pearlite mixture) and carbide-cementite phase are two main phase constituents of microstructure of the deposited metal. There are also areas of ledeburite eutectics located in the fusion zone and having honeycomb structure, that is character for low-alloyed cast iron of hypoeutectic composition. Carbide-cementite phase cannot be formed in all interaxial spaces of dendrites of solid solution in absence of boron, therefore, it looks like broken (non-solid) network in the section plane.

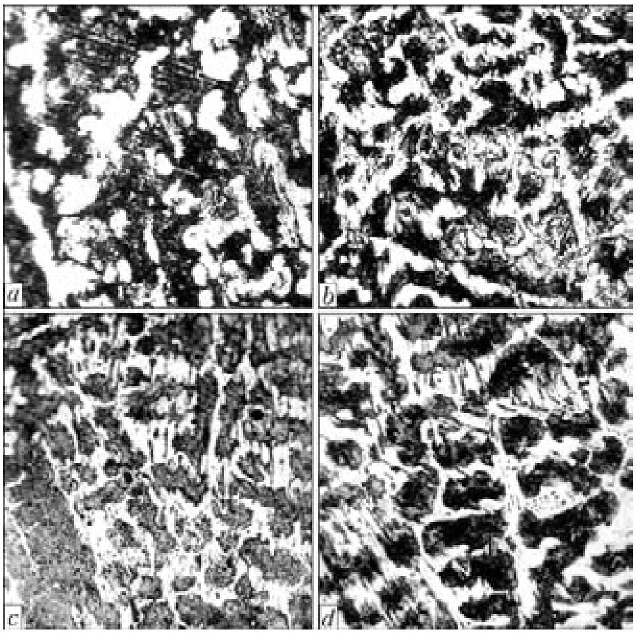

Figure 2. Microstructures (×640) showing influence of boron on morphology of carbide-cementite phase: *a* — without boron; *b* — 0.07; *c* — 0.13; *d* — 0.21 wt.% B

Boron microalloying makes significant influence on all structural constituents of the deposited cast iron. This influence becomes noticeable already at 0.03 wt.% B, and the most intensive changes take place in 0.07–0.15 wt.% interval of boron concentration. The structure of deposited cast iron changes insignificantly at boron content of more than 0.2 wt.%. Density of dendrite structure increases that is shown by decrease of size of solid solution grains from 100–112 (for deposited sample without boron) to 80–100, 64–80 and 32–48 μm for the samples containing 0.07; 0.13 and 0.21 wt.% B, respectively (Figure 1). Carbide-cementite phase, precipitating along the interaxial spaces of dendrites, also undergoes significant changes. It becomes less broken and solidifies in a form of solid network with thinned and widened areas (Figure 2). Width of areas of the carbide-cementite network in the deposited sample without boron makes 48–96 μm. Width of thinned areas equal 16–32, 8–16 and 3.2–2.4 μm and widened ones are 64–82, 48–64 and 32–40 μm at boron content of 0.07; 0.13 and 0.21 %, respectively.

Fusion zone in the investigated depositions has a structure of metal re-crystallized from solid-liquid state with presence of ledeburite colonies character for cast iron hardfacing. Ledeburite colonies in the section plane merge in a solid chill band at boron absence. Depth of regions of ledeburite areas achieves 600–800 μm in separate places of the fusion zone. Number of regions occupied by ledeburite reduces and character of their distribution becomes irregular with boron introduction. Maximum effect is achieved at 0.18–0.20 wt.% B. At that, sizes of ledeburite colonies in depth reduce up to 300 μm and level of their dispersion increase (Figure 3).

It should be noted that areas of structure of the deposited metal attached directly to the zone of complete melting have more differential structure than central areas of the deposited layer. Dendrites of solid solution solidify in this areas and have axles of the third order, interaxial distances of which have the following dependence on boron content (average values), i.e. without boron — 80 μm, 0.07 % B — 64; 0.13 % B — 48; 0.21 % B — 32 μm.

Modification by boron, except for structural changes, influences the hardness of deposited metal HV^A and microhardness of grains of solid solution HV^K, while microhardness of carbide phase HV remains virtually without changes (Figure 4). Increase of density and spreading of the grain boundaries strengthened by boron is probably connected with the rise of hardness of the deposited metal at insignificant

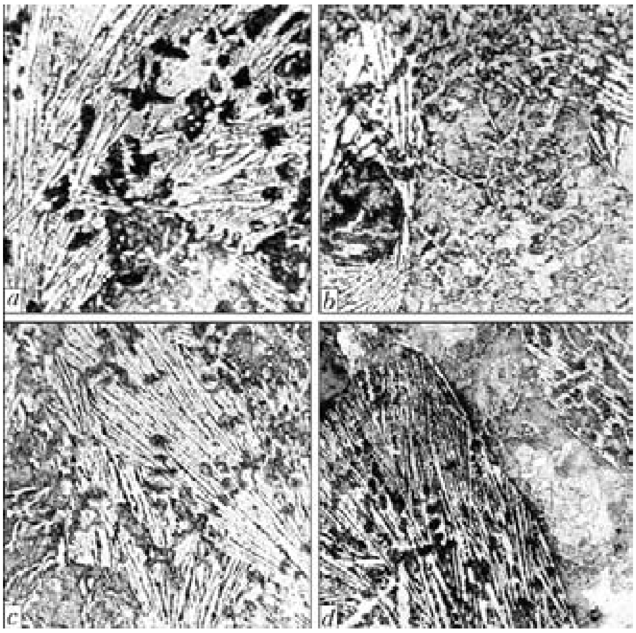

Figure 3. Microstructures (×200) of deposited metal with various dispersion of ledeburite colonies and boron content: *a* — without boron; *b* — 0.07; *c* — 0.13; *d* — 0.21 wt.% B

reduction of hardness of products of austenite decay, that does not contradict the theory of modification of cast iron using SAE [2, 4]. Anisotrophy of hardness values Δ (difference between the largest and the smallest hardness values) is also reduced. ΔHV and ΔHV^A values reduce from 640 and 700 (in deposit without boron) to 140 and 210 MPa (in deposit containing 0.21 % B), respectively. At the same time, ΔHV^K remains virtually on one level and makes 140–158 MPa independent on boron content. Microhardness of ledeburite colonies in the fusion zone increases with the rise of boron content from 6600–7300 (without boron) to 8500–9300 MPa (0.21 % B), that is caused by its influence on the level of ledeburite dispersion.

Thus, obtained data indicate that the minor additions of boron have significant modifying effect on all structural constituents of the deposited cast iron and homogeneity of values of their hardness.

Dual character of influence of boron on the processes of initial solidification can explain its determined significant effect on increase of crack resistance of the deposited cast iron. Presence of boron, from one side, results to significant reduction of grain sizes, increase of density, homogeneity and spread of solidified dendrites of solid-solution and carbide-cementite phase, i.e. formation of fine differential structure with developed network of grain boundaries reinforcing alloy with high strength closed frame. From the other side, the minor additions of SAE, in particular boron, adsorb on the boundaries or sections of crystallites, where concentration of vacancies and lattice distortions [2–4 et al.] is the highest one. At that, further growth of microcracks stops after their rise from the fusion zone in adjacent regions of the deposited metal with fine grain, differential structure and grain boundaries reinforced with boron.

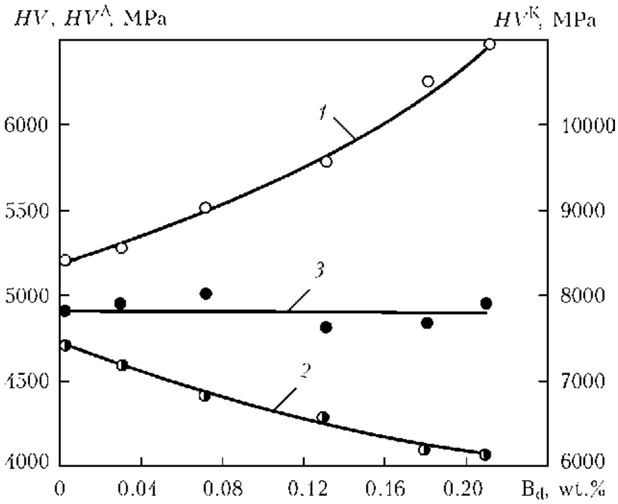

Figure 4. Influence of boron content on macrohardness of deposited metal HV (*1*), of grains of solid solution HV^A (*2*) and carbide-cementite network HV^K (*3*)

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TECHNOLOGY AND NEW GENERATION OF EQUIPMENT FOR FLASH BUTT WELDING OF ADVANCED HIGH-STRENGTH RAILS FOR CONSTRUCTION AND RECONSTRUCTION OF HIGH-SPEED RAILWAY LINES

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Presented are the technology and a new generation of equipment for flash butt welding of high-strength rails for construction and reconstruction of high-speed railway lines, based on the use of the pulsed flash butt welding process.

Keywords: *flash butt welding, pulsed flashing, computerised control system, technology and equipment, rail string, continuously welded rail track*

In the last decade the majority of industrialised countries have been intensively reconstructing their railroads, this being caused by increase in their traffic density and speed. For this the use is made of increased-strength rails with higher wear resistance. Specification requirements to the precision of a rail track determined by permissible deviations from its specified sizes have substantially grown. Meeting of these requirements motivated to a considerable degree the development efforts conducted in the world leading countries and aimed at improvement of the rail welding technology.

Rails laid down in main lines are welded primarily by the flash butt method under factory conditions for manufacture of long-length (200–800 m) rail strings, or under field conditions for their laying down and repair of continuously welded rail track.

For over 50 years the E.O. Paton Electric Welding Institute has been active in development of the technologies and equipment for flash butt welding under factory and field conditions. The world-first mobile machines of the K155 type for flash butt welding of rails were developed by the E.O. Paton Electric Welding Institute and successfully applied in railroads of the USSR as far back as the early 1960s. Commercial manufacture of the machines based on the developments of the Institute was mastered by the Kakhovka Factory for Electric Welding Equipment (KZESO). This cooperation continues to advantage up to now. By 2000, KZESO had mastered several generations of mobile rail welding machines of the K255L, K355A-1 and K900 types, as well as stationary rail welding machines of the K190 and K190PA types. Design of these machines is based on the use of the continuous flash butt welding technology with program control of the main process parameters [1].

The technology developed by the Institute is based on the new principles of control of the flashing process during flash butt welding, which allowed a 2–3 times decrease in power consumption, 1.5–2 times reduction in the welding time compared to the resistance heating welding process, as well as a stable and uniform heating of the rails across their sections. Several hundreds of such machines manufactured by KZESO have been successfully operated up to now not only in the CIS countries but also in many countries all over the world.

With use on the railroads of high-strength rails KF («Azovstal», Ukraine), E76F and K76T (Nizhnetagilisky (NTMK) and Novokuznetsky (NKMK) Metallurgical Works, Russia, U75V (PIETC, China) and BS113A (Corus British Steel), Great Britain), the need arose for substantial upgrading of the welding technology and the equipment required to implement it. Strength indices of metal grew by a factor of 1.3–1.5 (Figures 1 and 2), whereas requirements to ductile properties remained at the previous level according to the specification values.

As established in the course of the investigations conducted by the Institute [2], the required quality of the welded joints on high-strength rails can be achieved by using a highly concentrated heating in welding and a strictly balanced energy input (Figure 3). It should be noted that comparatively small deviations in heating from the optimal distribution of temperature lead to deterioration of indices in mechanical tests.

Decrease in energy input and, therefore, temperature in the near-contact zones of the weld (see Figure 3, fragment 1) leads to formation of fine oxide structures along the welding line. An increased energy input (Figure 3, fragment 2) causes coarsening of grain

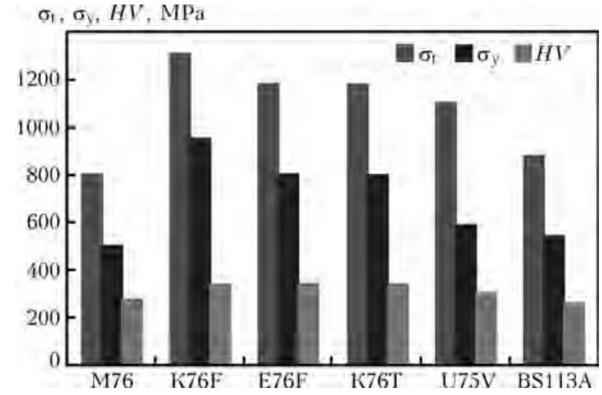

Figure 1. Strength properties of new rails

and formation of solid ferrite network along its boundaries.

To achieve the optimal thermal cycles, the Institute developed the welding technology called pulsed flash butt welding, which was patented in Ukraine [3] and in the world leading countries, such as Russia, USA, Great Britain and China. Multiple-factor regulation of the spark gap existing between the parts in contact during flashing, as well as of instantaneous values of voltage, provides intensification of contact heating, at which the metal losses for flashing are decreased and the efficiency is increased compared to the canonical processes of continuous flashing or intermittent resistance heating. The time of heating and allowances for flashing are reduced by a factor of 1.5–2.0. Production of sound joints is ensured at a smaller width of the HAZ metal (Figure 4).

The automatic system was developed and algorithms of multiple-factor regulation of main parameters of the flashing process were determined, thus allowing the preset level of energy input to be maintained during welding independently of changes in service conditions of the machines (quality of preparation of rails for welding, fluctuations of mains voltage, ambient temperature, etc.). The set program of regulation of the parameters is automatically corrected (adapted) if operational conditions of the machines change. As seen from Figure 5, the use of the optimal parameters (Figure 5, *I*) and automatically corrected parameters (Figure 5, *II*) in fluctuations of the mains voltage provide the specified temperature field and the required quality of the welded joints.

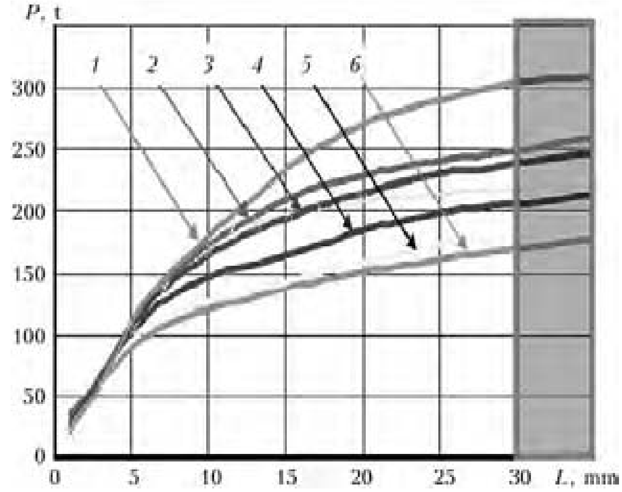

Figure 2. Dependence of load in static bend tests on sagging of rail (minimal permissible value of sag — 30 mm): *1* — NKMK, NTMK E78KhSF (Russia, 2006–2012); *2* — NKMK, NTMK E76F, K76F (Russia, 2006–2012); *3* — NKMK, NTMK E76F, K76F (Russia, 2003); *4* — Azovstal KF (Ukraine, 2011–2012); *5* — U75V (China, 2003–2012); *6* — Azovstal M75 (Ukraine, 1985)

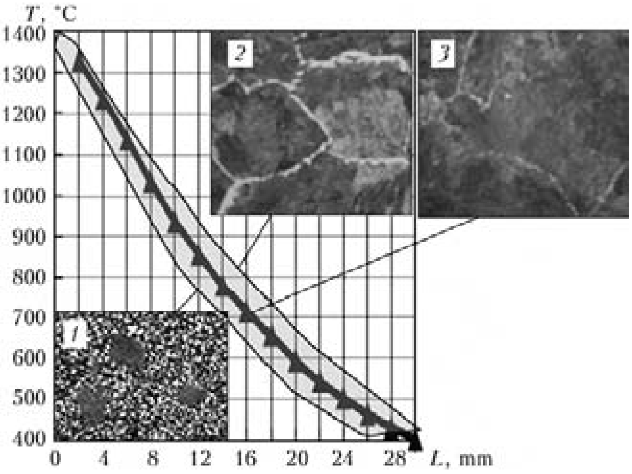

Figure 3. Distribution of temperature in welding of rails R65: *1* — zone of formation of oxide inclusions along the welding line; *2* — zone of overheating (coarse grain with ferrite precipitations along its boundaries); *3* — optimal structure

The problem of automation of some auxiliary operations accompanying production of continuously welded rail tracks was also solved in development of the systems for automatic control of the pulsed flashing process. In repair of the continuously welded rail tracks it is necessary to weld two fixed strings of an unlimited length. According to the accepted technology, an insert of rather big length (not less than 6 m) was welded to the strings with a preliminary bend required to compensate for shortening during welding. This operation is labour-consuming, and upon its completion it is necessary to restore the preset temperature-stress state of a string and geometric dimensions of a track. The calculated range of variations in the ambient temperature (60–90 °C) for a period of operation of the tracks is used in the majority of the

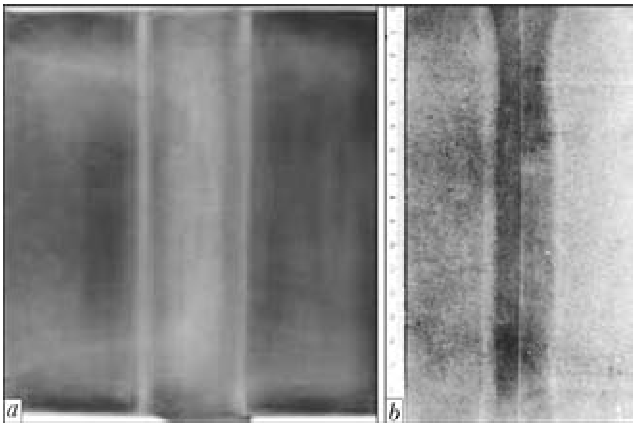

Figure 4. Macrostructure of welded joints on rails E76F: *a* — continuous flashing; *b* — pulsed flashing

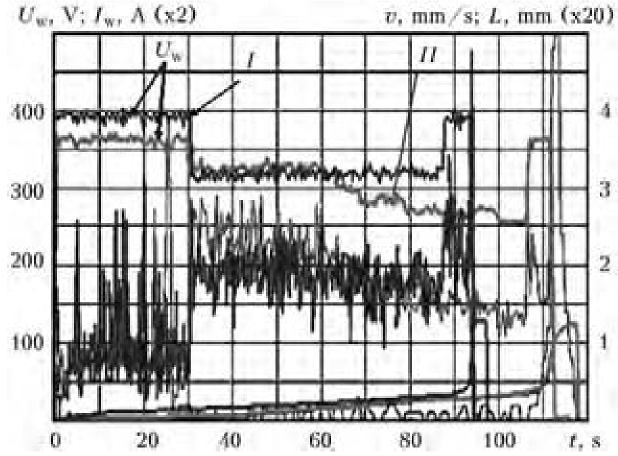

Figure 5. Record of main welding parameters with pulsed flashing: *I* — optimal mode; *II* — adaptive mode

world regions for construction of the continuously welded rails. Accordingly, internal stresses (tensile or compressive, depending on the period of operation) form in the rigidly fixed rail strings. The many years' experience evidences that the compressive stresses causing distortion of geometric dimensions of the rail string or its damage present the most serious hazard.

A new technology for welding of the insert without bending was tested with participation of the Institute. Required shortening in welding is provided due to tension of the string welded, which is freed from sleepers in a limited region (no more than 50 m). After welding the tensile stresses are induced in the string. The value of these stresses can be set precisely by varying the size of the preliminary gap between the ends of the strings prior to welding. Welding of long strings of the continuously welded rail tracks with tension makes it possible to set the most optimal parameters for their service at the ambient temperature changing during operation of the rails. If in repair or construction of the continuously welded rail tracks the value of the tensile stresses is set at a level exceeding that of the probable compressive stresses, the latter will not form in the rails during their entire service life. The similar problem arises in welding of strings of an infinite length in construction of new continuously welded rail tracks. These problems were solved owing to the development of automatic multiple-factor regulation of all parameters of the pulsed flash butt welding process, allowing for the auxiliary operation of tension of the rail strings welded. In welding, in addition to the parameters determining the welding conditions, also the data on the ambient temperature and required level of set tensile stresses in a string welded are loaded into the computer.

The use of the new technology for welding of high-strength rails, combined with their tension, required the development of new generations of the rail welding machines characterised by much higher upsetting forces and equipped with built-in mechanisms for removal of the weld reinforcement in hot state. All of the above innovations of the new technology for welding of high-strength rails and multiple-factor regulation systems were used as a base for the development of a new generation of mobile and stationary rail welding machines. This was achieved by employing the advanced computer facilities, fast-acting hydraulic drives and high-capacity systems for electronic control of welding parameters.

The new generations of the mobile machines comprise the upsetting drive (Table) that develops the 2–2.5 times higher forces than machines of the previous generations (K900 type). Besides, they are equipped with devices for automatic cutting of flash in the hot state. The rails are kept in the clamped state after welding, which prevents the probability of damage of the weld due to the effect of tensile stresses induced in a string after welding in the heated metal zone. Despite a substantial increase in power of the clamping and upsetting drives, weight of the new machines and their dimensions increased insignificantly, which made it possible to employ them in available

Specifications of stationary and mobile rail welding machines produced by KZESO

Parameter	K900	K920	K921	K922-1	K922-2	K930	K1000	K1100
Rated mains voltage, V	380	380	380	380	380	380	380	380
Maximum secondary current, kA, not less than	18	67	67	67	67	67	84	84
Rated power (duty cycle 50 %), kV·A	150	211	236	210	210	210	300	300
Working pressure in hydraulic system, MPa	100	125	210	210	210	210	160	160
Upsetting force, kN	450	1000	1500	1200	1200	1200	900	900
Clamping force, kN	1350	2500	2900	2900	2900	2900	2000	2000
Stroke of mobile part of machine, mm	70	100	150	100	150	200	100	115
Weight of machine, kg	2700	3000	4100	3100	3100	3450	8800	8800
Time of continuous flash butt welding of rails R65, s	180–220	–	180–220	–	180–220	180–220	180–220	180–220
Time of pulsed flash butt welding of rails R65, s	60–120	60–100	60–120	60–120	60–120	60–120	60–120	60–120

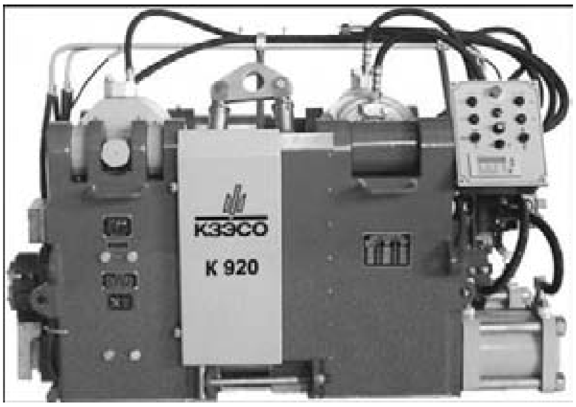

Figure 6. Machine K920

mobile rail welding systems without substantial reconstruction.

The first machine K921 for pulsed flash butt welding of rails with tension was developed by the E.O. Paton Electric Welding Machine in 2001. It was manufactured by KZESO in cooperation with «Norfolk Southern» (USA). Its application and optimisation of the rail welding technology were performed with participation of the Institute on railroads belonging to this Company. The technology was successfully applied, and different variants of implementation of welding with tension were verified. Over tens of such machines have been operated and efficiently utilised up to now. Flash butt welding of rail strings of an unlimited length, i.e. up to several hundreds of kilometres, without bolted joints was performed for the first time in the world practice. According to the available data, the total length of the unlimited-length rail tacks continuously welded by the Company is over 10,000 km.

In the last decade the Institute has continued working on the developments aimed at upgrading of the equipment for field and factory welding of rails to be used in different world regions.

In 2001–2005, machines of the K920 type (Figure 6) and two modifications of machines K922 (Figure 7) were developed for welding of rails in the CIS countries. Characteristics of these machines (upsetting and clamping forces, dimensions) were optimised with allowance for the existing repair and construction technologies, as well as for the available mobile rail welding systems. In particular, the weight and dimensions of the machines were substantially (1.5 times) decreased compared to the first pilot sample K921. They found wide application for repair and reconstruction of railroads in Ukraine and Russia. The pulsed flash butt welding technology was approved by the standards of railroads of Ukraine and Russia as the basic one for welding of high-strength rails. 18 machines K922-1 and 12 machines K1000 are in operation in Ukraine. Over 50 machines K922 were supplied to Russia. Machines K922 supplied to China (15 pieces) are very efficiently utilised. They were applied primarily for construction of high-speed railway lines. During the last 5 years the range of application of these machines has been considerably widened. Specialists of the Institute render the required consultation assistance in optimisation of the technology for welding of different types of rails and setup of the equipment. Different schemes of arrangement of the work in welding of rails under erection conditions are used. Machine K930 (Figure 8) providing a large length of tension of strings was developed for a more complete stabilisation of the temperature-stress state in unlimited-length rail sections.

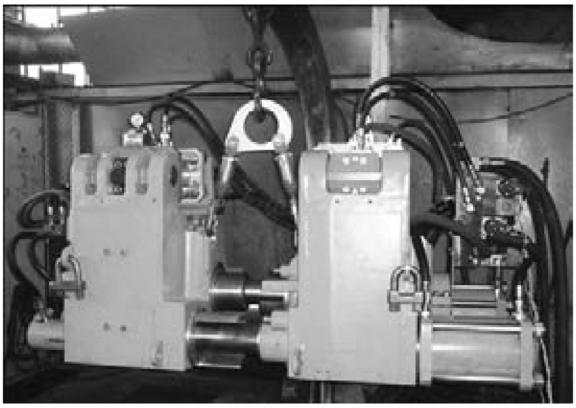

Figure 8. Machine K930 for welding of unlimited-length rails with tension

Modern mobile rail welding systems manufactured by KZESO are self-propelled machines that are either rail-mounted — KRS5 (Figure 9), or of a combined type — KSM005 (Figure 10), which allows them to

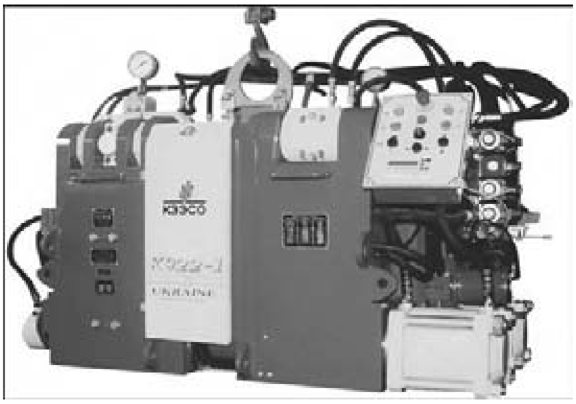

Figure 7. Machine K922-1

Figure 9. System KRS5

Figure 10. System KSM 005

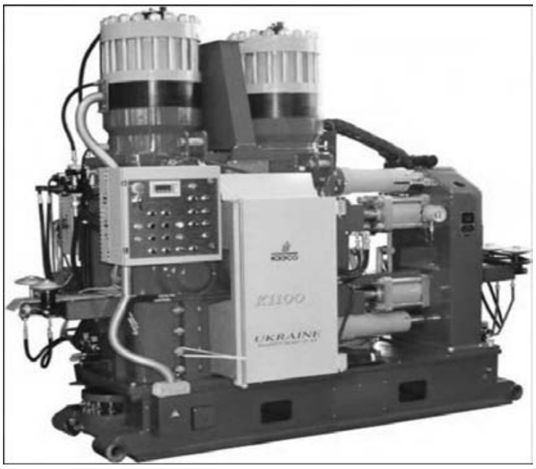

Figure 11. Machine K1100

be moved both on rail tracks and on highways or earth roads.

In addition to rail welding machines, the mobile systems comprise also diesel generators with a capacity of up to 200–300 kW, hydraulic rams, auxiliary equipment for preparation of rails for welding, and non-destructive test systems. Mobile systems of this type, where machines K920 and K922 are used, are employed on railroads of Europe, by Company «Holland» in the USA, Company «Network Rail» in Great Britain, as well as in China, Australia, Brazil, Taiwan, Malaysia, India, Turkey, Saudi Arabia and Thailand.

To raise the productivity of labour in reconstruction and construction of railway tracks, the rails are preliminarily welded into long-length strings from 200 to 800 m long, and then they are transported to the laying-down location. Welding is performed in stationary or semi-stationary shops by using stationary welding machines. In the last decade the Institute has developed a new generation of stationary high-strength rail welding machines K1000 and K1100 (Figure 11), which are based on the use of the pulsed-flash butt welding technology. The machines are characterised by a high productivity (the time of welding the maximal-section rails is no more than 70–120 s) at a power of 250 kV·A, this being almost twice as low as that of the known foreign stationary rail welding machines. The machines provide a high accuracy of alignment of the rails welded, which is especially important for welding of rail strings laid down into high-speed tracks. The machines perform automatic cutting of the weld reinforcement in the welding zone, while the hydraulic drives of the machines provide the increased upsetting forces required for welding of high-strength rails.

The computerised control systems of the machines ensure consistent reproducibility of the preset pulsed flash butt welding parameters and perform operational monitoring of the quality of the joints. The systems estimate the quality immediately after welding. Compared to the known machines, machine K1000 has smaller weight and dimensions, which allows using it in arrangement of semi-stationary shops for welding of rail strings.

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APPLICATION OF THERMAL BARRIER COATINGS FOR INTERNAL COMBUSTION ENGINES (Review)

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Literature data on application of thermal barrier coatings for protection of internal combustion engine components have been generalized. The methods used to apply thermal barrier coatings and materials used to deposit them are considered.

Keywords: *thermal barrier coatings, internal combustion engines, parts of piston-cylinder group, plasma spraying, partially stabilized zirconium dioxide*

At present the main kind of engines used in the drives of automotive, ship and railway transportation, agricultural machinery and quite a number of other machines and units are internal combustion engines (ICE) [1].

The main causes for lowering and loss of ICE serviceability are abrasive wear in friction pairs (piston rings and sleeves, crankshaft slide bearings, distribution shaft cams, etc.), cavitation wear (cylinder sleeves) and corrosion-mechanical wear (valve disc and seat) [1]. In addition, quite important is effective insulation of the combustion chamber with thermal-barrier coating (TBC) which enables redistribution of dissipated heat in such a way as to minimize its losses through the cooling system and exhaust gas removal system. Piston corrosion is caused by vanadium oxide and sulphide precipitates that are highly aggressive at temperatures of the surface of combustion chamber parts (400–500 °C). Improvement of antifriction properties of the parts allows lowering friction losses, which in the above components are equal to 50 % of total mechanical losses in the engine, and, thus, increasing the cost-effectiveness of its operation. The most promising method to lower the temperature of ICE parts, improve wear resistance of friction pairs, and protection from corrosion, is development of thermal barrier, wear- and corrosion-resistant coatings on part surface. Figure 1 shows car parts with TBC.

SULZER METCO is the best known abroad company involved in development and sale of equipment and manufacturing of consumable materials for deposition of various-purpose coatings. Given below is the information on coating materials most often applied for coatings used for repair of automotive parts. At repair of braking system parts (brake discs, brake blocks) plasma coatings from $Al_2O_3{\cdot}3TiO_2$, Ni5Mo5.5Al and molybdenum powders are used to improve the braking process, lower the weight, and extend the service life of discs and blocks. For engine system parts exposed to wear in service (piston rings, diesel injector, distribution shaft, crankshaft) plasma coatings from molybdenum and Mo–NiCrBSi powders, flame coatings from Fe38Ni10Al and Fe13Cr wires, coatings applied by arc metallizing from (WC–12Co)38.8Ni6Cr wire and coatings applied by supersonic flame spraying from Cr_3C_2 and Cr_3C_2–NiCr powders are used, which ensure high jamming resistance, high wear resistance, reduced friction, saving on costs, and extension of component service life. At corrosion (valve stem, exhaust sensor) plasma coatings from spinel powders and coatings from aluminium wire spray-deposited by arc metallizing are applied, which extend the valve life and ensure oxygen control. At oxidation (oxygen sensors) plasma coatings from ceramic powders and at high temperatures (piston top) — plasma coatings from ZrO_2–Y_2O_3 powders are applied for erosion protection, which ensure lowering of surface erosion and heat losses, thermal insulation, increase of engine operation effectiveness, and extension of piston operation term. To avoid weight increase because of heavy cast iron inserts,

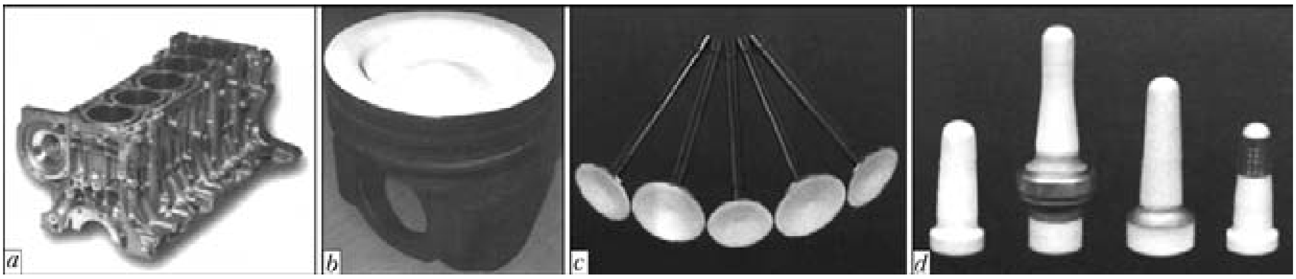

Figure 1. ICE parts with TBC: *a* — engine cylinders; *b* — piston; *c* — exhaust valves; *d* — exhaust sensor, oxygen sensor

plasma coatings from Mo, MoFe, Fe and other powders are applied on engine cylinders, which reduce engine dimensions and oil and fuel consumption. In case of an adhesion problem on the interface between the cylinder sleeve and cast aluminium block of the cylinder, coatings from AlSi wire, spray-deposited by arc metallizing and flame coatings from NiAl wire are applied, which improve the surface of aluminium casting and its functionality. In case of dielectric insulation (generator cover), plasma coatings from Al_2O_3 powders are used. For exhaust system components at increased heat radiation and higher temperature of exhaust gases plasma coatings from ceramic powders, flame coatings from aluminium wire for thermal insulation, thermal shielding, temperature lowering, and saving on costs are applied, and flame coatings from aluminium wire are applied under corrosion conditions on exhaust muffler to achieve a longer service life at low cost.

The main direction of increasing ICE power is raising the temperature and degree of working gas compression at fuel combustion [2]. Therefore, the problem of increasing working temperature in the combustion chamber due to lowering of heat losses in the cooling system is becoming urgent. The most promising method to solve this problem is application of TBC, at deposition of which engine operation mode is optimized, their efficiency is increased, and consumption of fuel and lubrication materials is reduced.

Development of TBCs for propulsion engineering is given a lot of attention in the USA, Japan, Great Britain, Germany and Norway. In CIS countries (Russia, Ukraine, and Belarus Republic) research is conducted on development of various coatings (including TBCs) to improve ICE effectiveness and reliability. At present, TBCs have found wide application in Ukraine for protection of blades of gas turbine engines (GTE) [3], while development of TBCs for ICE components is practically absent.

The main purpose of TBCs in ICE is lowering of heat losses in the combustion chamber and protection of the metal base from high temperature impact. As a rule, TBC consists of an insulating outer ceramic layer (upper) and metal layer (bond coat) between ceramics and base (Figure 2) [4, 5]. Thermal barrier functions are fulfilled by outer ceramic layer. The main function of the bond coat is plastic relaxation of stresses in the coating, arising because of uncoordinated change of the volumes of ceramic and metallic materials at item heating and cooling.

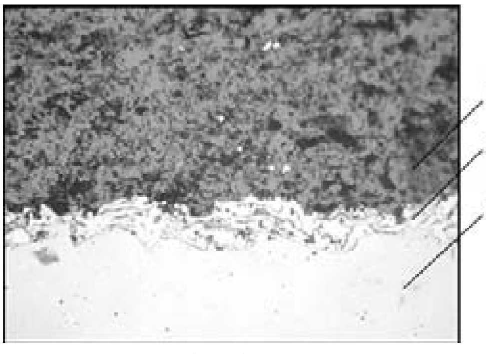

Figure 2. Microstructure (×200) of two-layer TBC: *1* — ceramic layer; *2* — metal bond coat; *3* — base

Ceramic materials mainly used for TBCs are zirconium dioxide, partially stabilized by oxides (7–8 % Y_2O_3, 22 % MgO, 25 % MgO, 5 % CaO), aluminium oxide, and chromium oxide [5, 6]. Zirconium oxide partially stabilized by yttrium oxide became the most widely accepted [4, 5]. Wide application of ZrO_2 is due to its low coefficient of heat conductivity ($1.95\ W\cdot m^{-1}\cdot K^{-1}$), high coefficient of linear expansion ($\alpha = (5.0–5.6)\cdot 10^{-6}\ K^{-1}$), high-temperature strength and high fracture toughness.

Used as bond coat material are high-temperature resistant alloys based on MeCrAlY (Me = Ni, Co, Ni–Co, Fe), as well as NiCr. The most widely accepted for this purpose is NiCrAlY that is due to its high oxidation resistance (up to 900–1000 °C) and good ability to relax stresses in the coating.

Such spraying methods as plasma method (in open air [1, 2, 4, 5, 7–13], at low pressure or in inert-gas atmosphere [5, 8]) are used for deposition of functional protective coatings.

The main method for deposition of TBC ceramic layer is plasma spraying in air (up to 90 % of developments) [5]. Predominant acceptance of plasma spraying of TBCs is due to its high efficiency and versatility that allows application of metal and ceramic materials of specified chemical and phase composition in the form of coatings of a considerable thickness.

High-temperature bond coat is deposited by the methods of plasma spraying in inert atmosphere or dynamic vacuum, and electron beam vacuum deposition to prevent bond coat material oxidation during spraying.

Up to now most of the developments on coatings of ICE parts falls to the share of piston group (more than 90 %, including piston rings at about 70 %) [2, 5, 7, 8, 10–13].

It is established [2] that one of the important factors of service properties of coatings from ZrO_2 is the spray-deposited layer thickness. Coatings from ZrO_2 0.1–0.5 mm thick on cast iron piston rings lower the temperature of piston «hot» points by 45–50, piston top temperature — by 25, and in the region of upper piston ring — by 10 °C, have an equalizing impact on piston head temperature field, that promotes lowering of thermal stresses, which are the causes for cracking in cast iron pistons. Effectiveness of coating application is the greater, the higher the piston temperature at operation without the coating. After 9490 h of operation ZrO_2 coatings of the above thicknesses (0.1–0.5 mm) did not have any spallations, and after 12,854 h of operation small spallations appeared on the top edge, and coatings continued operating up to 22,548 h (6 years of operation) [2]. At deposition of ZrO_2 coating on a steel piston, heat transfer in the cooling system decreased by 26 % that allowed, in an engine with lower heat removal, reducing radiator working surface by 21 % and lowering power consumption of cooling ventilator by 3 kW [8]. In [12] it is established that coating on an aluminium piston from ZrO_2 1 mm thick does not have any damage of the layer after 50 h of operation, and at coating thickness of 2 mm crumbling and spallation of the ceramic layer are observed. Coating on a ship engine aluminium piston from ZrO_2, stabilized by 5 % CaO, remained intact after 3.5 years of operation, although it had a carbon layer on it [7].

Plasma coatings from Al_2O_3 0.45–0.5 mm thick on a piston lower the temperature in the top center by 31, and in the piston ring area — by 12 °C. Al_2O_3 TBCs on pistons showed a good performance after 500 h of operation, no fractures were observed inside the chamber, while in cast iron pistons slight spallations in TBCs on top edge developed only after 12,854 h of operation, but coatings continued to operate up to 22,548 h (6 years of operation). Al_2O_3 coating more than 1 mm thick on a cast iron piston turned out to be nonserviceable, but at smaller thicknesses it operates without fractures. On aluminium pistons the serviceable thickness of this coating is not more than 0.4 mm at piston preheating before coating deposition. Without preheating of the aluminium base the above thickness is nonserviceable, because of considerable tearing and tensile residual stresses, as well as cyclic thermal stresses arising at operation in the diesel engine [2].

Two-layer coatings of the total thickness of 1 mm from stabilized ZrO_2–24 % MgO and FeCrAlY bond coat on an aluminium piston did not fail after testing for 5000 h [10]. Thermal cycling tests at the temperature from 0 up to 950 °C of two-layer coatings from ZrO_2–20 % MgO + NiCrAlY, ZrO_2–8 % Y_2O_3 + Ni–CrAlY, ZrO_2–25 % MgO + CoNiCrAlY, ZrO_2–20 % MgO + NiCoCrAlY of less than 1 mm thickness on aluminium pistons showed that TBCs have sufficient resistance relative to cyclic temperature variations. Coating fracture occurs because of oxidation of MCrAlY bond coat. Coating from stabilized ZrO_2–7/8 % Y_2O_3 showed higher resistance at the temperature above 1000 °C [9]. Two-layer coating on aluminium piston from stabilized ZrO_2–5 % CaO with 20Ni80Cr bond coat 1.5 mm thick cracks and breaks up after 50 h (2800 heating–cooling cycles) [12].

On cast iron piston two-layer coating from Al_2O_3 0.6 mm thick with NiCr bond coat 0.1 mm thick provides temperature lowering in the «hottest» points of piston top in the zone of the impact of flame plume by 40–48, and in the zone of piston upper groove — by 8–10 °C. On an aluminium piston a coating from Al_2O_3 with NiCr bond coat lowered the temperature by 15–20, and in the upper groove zone — by 5–7 °C [2].

Two-layer coating from stabilized ZrO_2–22 % MgO with NiCoCrAlY and NiCrAlY bond coats of approximately 0.4 mm thickness on the top of a cast iron piston remained unchanged after 500 h of testing, and coating from ZrO_2–8 % Y_2O_3 with NiCoCrAlY and NiCrAlY bond coats remained intact even after 9000 h of testing [11]. Coating from ZrO_2 of up to 2 mm thickness on the top of a steel piston reduces heat transfer into the cooling system by 30.4, increases effective power by 3.75, and reduces specific fuel consumption by 3.58 % [8].

On heads of pistons from high-temperature 2Kh13 steel Al_2O_3 and ZrO_2 coatings on NiCr bond coat of more than 0.4 mm thickness have small spallations after running for 163,332 km, and the rest of coating surface remains in good condition without cracks [2]. Two-layer coating from ZrO_2–7 % Y_2O_3 with NiCrAlY bond coat on aluminium piston head reduces specific heat removal by 30 %, fuel saving being 5–10 % [13].

Coatings of cermet composition are used to lower piston temperature and heat flows through the piston [2]. Coating of cermet composition ZrO_2–Ni 0.7 mm thick with higher heat conductivity has lower heat resistance than that from Al_2O_3 0.6 mm thick, so that its effectiveness is also lower. Heat resistance increases with increase of coating thickness, but not in proportion to layer thickness. Long-term testing for 917 h of cermet coating performance in the pistons showed that the coatings do not have any fractures [2].

Multilayer coatings of cermet composition with gradually changing coefficient of linear expansion have higher performance compared to purely ceramic coatings, and can be used with success on cast iron, steel and aluminium pistons. Multilayer coatings with ZrO_2–Ni ceramic surface layer 0.3–0.4 mm thick with NiCr bond coat 0.1 mm thick on aluminium pistons have operated for 397–1104 h in different modes [2].

Al_2O_3 coating 0.25–0.35 mm thick on cylinder sleeve withstood testing under the impact of thermal shocks without fracture, at 0.5 mm thickness it had no spallations during testing, but coating cracking under the impact of tensile stresses was observed in more heated areas [2]. Conducted thermal cycling testing of two-layer TBCs from ZrO_2 stabilized by MgO, Y_2O_3 and CaO oxides with CoNiCrAlY bond coat on cylinder sleeves at temperatures from 50 up to 1100 °C showed that coating from ZrO_2–7 % Y_2O_3 withstood 20,000 cycles, ZrO_2–20 % Y_2O_3 — 2500, ZrO_2–24 % MgO — 12,000, ZrO_2–5 % CaO — 3000 cycles, respectively. Two types of cracking — perpendicular (segmented) and parallel are found in ZrO_2–7 % Y_2O_3 coating with CoNiCrAlY bond coat after thermal cycling [7].

On cylinder head ZrO_2 coating 2 mm thick and two-layer coating from ZrO_2–24 % MgO with FeCrAlY bond coat do not have any traces of degradation and do not fail after testing for 5000 h [10]. When coating from ZrO_2 3 mm thick on cylinder bushing is used no crumbling or spallation of coating is observed after 50 h of operation [12].

Results of testing flat flame surface of cylinder cover with ZrO_2 coatings of 0.4–0.5 mm thickness showed that the coating slightly increases the temperature of cylinder piston and busing and leads to redistribution of heat flows passing through the parts [2].

Analysis of factors determining the thermal and mechanical stress level of exhaust valves shows the rationality of TBC application on exhaust valve discs [2]. TBCs on the valves lower not only the valve temperature, but, what is most important, the temperature gradients in the valve disc and, therefore, also thermal stresses in it. With increase of TBC thickness, decrease of temperature gradients becomes smaller. Coating ensures the greatest lowering of temperature gradients of the valve disc at its deposition not on the entire diameter, but on a diameter smaller than the full diameter by the size of chamfers. In the central part of valve disc ZrO_2 coating 0.5–0.6 mm thick lowers the temperature in the disk center by 60 and increases the temperature of valve edge by 15–20 °C [2].

Coating from ZrO_2 on exhaust valve was covered by hairline cracks after 180 h of functioning, that lowers the thermal stresses and leads to stopping of further breaking cracking along ceramics/metal interface. Valve continued operating without any considerable damage up to appearance of corrosion at fuel contamination, which led to formation of craters and after 800 h of operation ZrO_2 coating failed [7]. Testing of valves with coatings from ZrO_2 stabilized by oxides — 24 % MgO and 8 % Y_2O_3 — for 4000 h showed good service life of both the coatings on valve surface. Mass loss rate of ceramics as a result of erosion was higher for ZrO_2 stabilized by MgO than for ZrO_2 stabilized by 8 % Y_2O_3. At testing for 5000 h coatings on valves did not fail [10]. For greater lowering of temperature gradients in the valve it is rational to apply anisotropic coatings characterized by low heat conductivity in the axial direction of coating layer and greater heat conductivity along the coating layer. Such properties are characteristic for multilayer coatings consisting of alternating layers of ceramics and metal. Ceramic layers prevent passing of thermal flow from gases to valve disk, and metallic coatings transfer the heat from the center to edges of valve disk. At correct selection of composition and thickness of coating layer it is possible to achieve such a temperature field of the valve which ensures the smallest thermal stresses in it [2]. Three-layer coatings from ZrO_2–24 % MgO with NiCr and NiCrAlY bond coats 0.7 mm thick on exhaust valves lowered metal temperature by 50 °C. The smallest temperature lowering was recorded in the area of valve seat (because of circular seat water cooling) [10].

On valve sealing surfaces two-layer coatings from ZrO_2–8 % Y_2O_3 with NiCoCrAlY and NiCrAlY bond coats have localized small delamination in the upper part of ceramic coating after 500 h of testing. Coatings from ZrO_2–22 % MgO with NiCoCrAlY and NiCrAlY bond coats on valve sealing surface almost completely came off the valve surface after 500 h of testing, because of ZrO_2 destabilization at running of chemical reaction between MgO and sulphur, and after 9000 h of testing valve surfaces failed, and MgO concentration in the coating dropped to 3 % [11].

Analysis of experimental results shows that TBCs on combustion chamber parts, reducing heat removal, allow them to be better used for organizing the combustion process and improving the effectiveness of the engine [2]. At testing of coatings on combustion chamber parts, researchers focused on reducing heat removal into the coolant, and thus improving the effectiveness of ICE operation. TBC from ZrO_2 2.5 mm thick on combustion chamber increases engine effectiveness by approximately 7.5 %, and at 3 mm thickness heat losses through combustion chamber walls decrease by about 50 % [12]. Two-layer TBC from stabilized ZrO_2–8 %Y_2O_3 with NiCrAlY bond coat 2 to 2.5 mm thick on combustion chamber decreases the amount of energy consumed in coolant heating and lowers fuel consumption by the engine to 10 g/l, and the coating can stand more than 10,000 thermal shocks [12].

Analysis of the results of studies aimed at lowering ICE piston temperature at TBC application, depending on load level, boosting, rotation frequency, diesel engine dimensions and coating properties, leads to the conclusion that it is mainly determined by heat resistance of the piston and coating. Heat resistance of the piston depends on the design, diameter and heat conductivity of the material, and heat resistance of the coating — on its thickness and heat conductivity. Heat resistance of a coated piston is influenced to a certain extent by heat conductivity of the zone of coating contact with the part surface, as well as coating roughness. Smooth surface of the coating promotes greater lowering of piston temperature that leads to improvement of its cost effectiveness. In addition to the above factors, the nature of working process running has a certain influence on lowering of piston temperature at TBC application. Coating on piston top also leads to redistribution of heat flows through cylinder cover and bushing, increases the heat flow to cylinder cover and decreases the heat flow through the bushing (except for its upper girth). Thermal protection of these components not only lowers their temperature and thermal stresses, but also reduces heat removal into the cooling system, that should positively influence the engine efficiency and lowering of weight and overall dimensions of heat exchanger devices.

The main causes for fracture in the coating are thermal stresses, caused by temperature mode in the combustion chamber, piston top design, as well as thickness and physico-mechanical properties of the ceramic coatings proper. Fracture of two-layer TBC most often occurs in the interlayer zone, because of high compressive stresses in the coating. Fracture is also affected by perpendicular and parallel cracks in the coating. Perpendicular cracking, caused by tensile stress field, is believed to be favourable for coating fatigue life, as it relieves the stresses, allowing the coating to expand and contract, without experiencing any considerable shear stresses. Parallel cracking developing as a result of breaking shear stress leads to coating fracture.

Long-term service testing of engines with coatings on pistons revealed that coatings, lowering thermal stresses in the piston, allow increasing their reliability and service life to a considerable extent. Reducing the heat flow through the piston, the coating improves lubricating oil performance, thus preventing gumming-up of piston rings. At lowering of dynamic loads and piston temperature, the coating considerably reduces the wear of parts of cylinder-piston group. All this promotes extension of service life of the diesel engine and lubricating oil. TBCs increase the reliability and service life of pistons by not less than 1.5 times. These coatings lower the piston temperature and dynamic loads, and, hence also diesel engine noise and vibration, toxicity of their exhaust gases, wear and carbon deposits on parts of cylinder-piston group, and they also improve cost-effectiveness and lubricating oil performance, as well as reliability and service life of pistons as a whole.

On piston head TBC is also intended to ensure corrosion resistance of its material at high temperatures that reduces carbon deposition.

TBC on cylinder head increases exhaust gas temperature by approximately 30 °C and shortens the delay time of the moment of fuel ignition in the cylinder by approximately 10 %, compared to uninsulated engine.

On exhaust valves TBCs reduce the heat supply to the valve that allows maintaining the temperature on the seat surface below the threshold value of high-temperature corrosion in aggressive media.

Testing data showed that at TBC application the heat flow through the combustion chamber to the coolant can be reduced by approximately 30 %. As a result, it is possible to use a greater amount of heat from exhaust gases, for instance, for pumping. This results in higher total thermal efficiency. Higher average temperature will positively influence the combustion process and level of smoking exhaust.

TBC application on ICE parts ensures: up 11 % fuel saving; up to 20 % extension of engine life; reduction of exhaust toxicity for $NO_x < 5$; $CO < 15.5$; $HC < 1.3$ and for sooty exhaust < 0.10 g/(hp·h), of quantity of solid particles in exhaust gases by 52 %, engine smoking by 75 %, noise characteristics by 3 dB, engine temperature by 100 °C; extension of fatigue life of exhaust valves by 30 %; and lowering of engine cost due to application of less expensive and deficit material at other conditions being equal.

Thus, TBCs on the piston and other parts of the combustion chamber essentially improve diesel engine performance. «Rigidity» of the combustion process and maximum pressure at combustion are lowered, thus reducing the noise, diesel engine vibration and toxicity of exhaust gases. Increase of combustion speed in the main arcing phase increases the combustion efficiency and ensures a more cost-effective operation.

TBC application should be determined by their purpose for each concrete diesel engine. In each case, their maximum effectiveness can be achieved by varying the coating thickness and composition.

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MAIN TENDENCIES AT THE MARKET OF WELDING TECHNOLOGIES IN 2008–2011 AND FORECAST OF ITS DEVELOPMENT (Review)

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The data on the state-of-the-art of world production, consumption and market of welding technologies in the period of 2008–2011 and prospects of their further development are presented.

Keywords: *welding technology, production, consumption, market, economy, statistics*

The situation at the world market of welding technologies in 2008–2011 was changing rapidly. Its growth (35 %) in the period of 2007 – the I quarter of 2008 was followed by recession in the II–IV quarters of 2008 (10 %) which increased in 2009 (24 %). In 2010–2011 the growth of sales was observed at all regional and branch markets of welding technologies. However the majority of leading producers of welding technology goods could not achieve the level of sales of 2008.

According to the data analysis given in annual reports of companies – the leaders in producing welding technology goods, the greatest reduction of sales at the world market of welding technologies was observed in 2009. The volume of sales decreased on average by 35–40 % as compared to 2008. For instance, in the II quarter of 2009 ESAB decreased sales of welding equipment by 46 and welding consumables by 38 %, ITW did by 37.5 % in the first half of 2009, Thermadyne – in the I quarter of 2009 by 36 %, Lincoln Electric – in the first half of 2009 by 41 % as compared to the same periods of 2008.

The market growth began in the I quarter of 2010 when the volume of sales increased on average by 0.7 %. In general during 2010 the volume of sales of the leading world producers of welding technology goods as compared to 2009 grew by 13 (Air Liquide), 28 (Voestalpine AG–Boehler), 14 (ESAB), 20 (Lincoln Electric) and 14 % (ITW). In 2011 the volume of sales at the market of welding technologies increased in the first half of the year, and in the III quarter it was delayed. Therefore, the volume of sales of Lincoln Electric increased by 35 % over the 9 months of 2011, ESAB by 18 and Thermadyne by 19 %. In the IV quarter of 2011 the volume of sales was observed to be even more reduced. It is assumed that decrease of the latter at the market of welding technologies will continue also in the I quarter of 2012 [1–4].

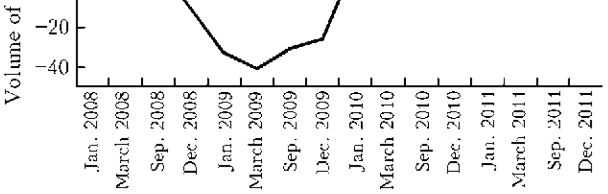

Figure 1. Volume of quarter sales of «Lincoln Electric» for the period of 2008–2011

Appealing to the quarter sales data of the leading world producer of welding technologies – Lincoln Electric (Figure 1), comprising 40 plants in 19 countries of the world and distribution network in 160 countries, it is possible to estimate tendencies at the world market of welding technologies for the period of 2008–2011. The volume of sales of this company in 2011 reached 2.7 bln USD which amounted about 16 % of the volume of sales at the world market of welding technologies [5].

Such fluctuations at the market of welding technologies for the period of 2008–2011 were observed in the time range on the regions and also types of welding technologies (consumables and equipment).

In regional section the greatest sales recession in 2008–2009 was observed in North America and Europe. According to the assessment of ESAB experts, the demand at the American market of welding products decreased by 18 % in 2008 and in the end of 2009 it did more than by 30 % which in total caused reduction of market almost by 50 % during that period. In 2008 the European market decreased less than by 3 % and in 2009 the market abrupt by 26 %. To compare, the demand at the markets of Asia fell only by 1 % in 2008 and in 2009 by 19 %. The markets of China, India, countries of Middle East, South America and Africa remained stable enough though some enterprises were forced to reduce the volume of products [1].

The data from «The Japan Welding News for the World» allow providing an adequate assessment of changes of sales volume in the main regions (countries) and segments of the world market of welding technologies for the period of 2008–2010. Tables 1–3 give data about the volume of consumption of main types

Table 1. Volume (thou t) and structure of consumption of welding consumables on the main world markets

Region (country)	Covered electrodes, %		Solid wire, %		Flux-cored wire, %		Consumables for submerged arc welding (wire + flux) and other, %		Total	
	2008	2010	2008	2010	2008	2010	2008	2010	2008	2010
China	60	57	25	26	4	6	11	11	2600	2700
Europe	13	12	64	56	11	18	12	14	680	540
North America	15	15	58	54	21	22	6	9	520	410
Japan	12	11	47	42	30	35	11	12	365	289
ASEAN countries	51	51	38	35	6	8	5	6	320	260
Korea	14	14	37	34	39	40	10	12	260	210
Russia and CIS countries	58	56	27	26	4	5	11	13	240	200
India	64	59	23	26	4	7	9	8	230	250
Central and South America	54	53	33	32	5	6	8	9	205	185
Middle East	58	59	27	26	5	5	10	10	130	160
Africa	68	62	22	25	4	5	6	8	85	130
Taiwan	30	29	48	46	17	18	5	7	80	70
Oceania	49	49	36	36	6	6	9	9	50	50
Hong Kong	59	58	26	26	5	6	10	10	20	20
									5785	5474

of welding consumables and welding equipment in the regions and countries of the world [6, 7].

The growth of welding consumables for the last years is astonishing. Thus, in 2004 the world consumption of welding consumables in quantitative estimation amounted about 3 mln t [8]. According to the assessment of Japanese experts the world consumption of welding consumables in 2008 reached another peak of 5.8 mln t, thus in four years it increased almost twice. In 2009 as a result of economic crisis the consumption of welding consumables decreased considerably in most countries and regions of the world — first of all in Europe and North America. However in the countries with growing economy (China, India, countries of Africa, Middle East, Turkey, Iran) the consumption of welding consumables continued its growth.

The growth of the world volume of consumption of welding consumables is observed in China and developing countries of the South Eastern Asia (India, Malaysia, Indonesia, Vietnam). China covers almost half of the whole world volume of consumption of welding consumables — 49 %.

The structure of consumption of welding consumables of developed and developing countries is remarkably different. In the developed countries of Europe, America, Japan, Korea the 2/3 of the volume of consumption of welding consumables refers to solid and flux-cored wires. Therefore in Europe, America and Japan the consumption of solid wire prevails, whereas in Korea flux-cored wire. The consumption of covered electrodes in these regions and countries does not exceed 15 % (mainly welding electrodes of special purpose).

In developing countries the volume of covered electrodes is great and varies between 50–60 %. However the structure of consumption of welding consumables in developing countries changes rapidly. In the last years the consumption of solid and flux-cored wires has been growing whereas volume of covered electrodes decreasing. This tendency remained also in the period of crisis 2009. It should be noted that also in developed countries during the period of crisis the decrease of consumption of welding consumables occurred mainly due to decrease of volume of covered electrodes and solid wire, whereas for example in Europe, in general (20 %) decrease of consumption of welding consumables in 2010 as compared to 2008, the growth of consumption of flux-core wire by 30 % was observed.

Though volume of sales grew in 2010, the world market of welding consumables did not reach the level of 2008. In 2011 the world economy, especially in Europe and some Asian countries (Japan, Korea) delayed the tempo of its development which negatively influenced the market of welding technologies. For example, in Japan the volume of consumption of welding consumables in 2011 decreased by 1.2 % as compared to 2010 and amounted 285.6 thou t. It occurred mainly due to decrease of demand on covered electrodes by 3.8 % [9].

The world market of welding equipment recovers very slowly after the crisis of 2009. The consumption of welding equipment in developed countries de-

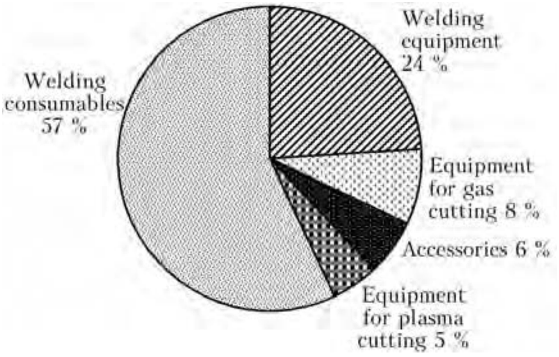

Figure 2. Structure of the world market of welding technologies in 2010 (without shielding gases, means of shielding and abrasive materials)

creased by 40–60 % as compared to 2008. The structure of the world market of welding technologies is presented in Figure 2. The fracture of the market of materials for welding and surfacing in 2010 amounted 57 % and that of welding equipment — 24 %. The leading positions at the market of welding equipment occupy technologies for inert gas arc welding (MIG). Its fracture occupies 40 % of the whole market of welding equipment. This market segment has a quite good dynamics of development, especially automated welding equipment for synergetic MIG welding. This type of equipment surpasses devices for TIG welding in 3–4 times and substitutes them at the market of welding equipment.

The equipment for gas welding and cutting amounts 5–10 % of the market. Its volume is constantly decreasing and, where possible is replaced by electric welding. An exception here is the branch of ship building where applying electric welding is dangerous [10]. The main fracture at the market of welding equipment covers equipment for arc and resistance welding. As is seen from the data of Tables 2 and 3 in 2010 the world consumption of welding equipment for arc and resistance welding amounted in quantitative estimation only 74 % of consumption level of 2008 and in cost one 65 % [6, 7].

The volume of China in the all-world quantitative volume of consumption of welding equipment for arc and resistant welding amounts about 37, European countries — 14, North America — 10 %. In the cost estimation the volume of consumption of European countries — 25, China — 20 and North America — 18 %. The data given above allow estimating the structure of consumption of the main types of welding equipment in those regions. Thus in China and developing countries the demand on cheap arc welding equipment prevails. In the structure of consumption of welding equipment (see Table 2) the volume of equipment for arc welding in China and developing countries amounts in quantitative estimation 98 % and in cost one (see Table 3) — about 90 %. In the developing countries the volume of equipment for resistance welding is considerably higher and amounts relatively 6–8 and 26–34 %.

In 2010–2011 the following tendencies on the regional markets of welding technologies were distinguished. The situation on the market of welding technologies of European countries was diverse. One of the first countries showing its growth of welding technologies market was Germany producing the third part of all welding products in Europe. According to the data of the German welding society, in 2010 it was produced welding technologies for 2.2 bln Euro which overcame the level of 2009 by 7.5 %. The major part of issued production (per 1.8 bln Euro) were machines and devices, however growth of their pro-

Table 2. Quantitative volume (pcs) of consumption of equipment for arc and resistance welding in 2008 and 2010

Region (country)	Arc welding		Resistance welding		Total	
	2008	2010	2008	2010	2008	2010
China	477,000	430,000	8,000	8,500	485,000	438,500
Europe	216,000	150,000	18,000	11,000	234,000	161,000
North America	170,000	108,500	11,500	6,500	181,500	115,000
Japan	120,500	53,150	8,900	3,560	129,400	56,710
ASEAN countries	101,900	67,000	3,400	2,500	105,300	69,500
Russia and CIS countries	83,400	55,000	2,000	1,400	85,400	56,400
India	78,800	65,000	2,100	2,300	80,900	67,300
Korea	72,300	45,000	4,300	2,600	76,600	47,600
Central and South America	69,900	56,000	5,100	4,000	75,000	60,000
Middle East	40,400	36,000	1,000	900	41,400	36,900
Africa	32,000	31,000	700	750	32,700	31,750
Taiwan	26,700	19,500	450	450	27,150	19,950
Oceania	19 000	17 500	500	500	19,500	18,000
Total	1,507,900	1,133,650	65,950	44,960	1,573,850	1,178,610

Table 3. Cost volume (mln USD) of consumption of equipment for arc and resistance welding in 2008 and 2010

Region (country)	Arc welding		Resistance welding		Total	
	2008	2010	2008	2010	2008	2010
Europe	900	589	364	207	1264	796
North America	752	465	242	131	994	596
China	702	589	57	57	759	646
Japan	580	262	156	56	736	318
Korea	163	96	88	50	251	146
ASEAN countries	186	115	31	21	217	136
Central and South America	110	87	47	31	157	118
Russia and CIS countries	136	85	15	11	151	96
India	126	100	17	17	143	117
Middle East	106	90	13	11	119	101
Africa	58	54	6	7	64	61
Oceania	57	50	7	7	64	57
Taiwan	41	29	4	4	45	33
Total	3,917	2,611	1,047	610	4,964	3,221

duction reached only 2.7 %. The cost volume of production of welding and filler materials was only 459 mln Euro however growth of production exceeded 31 %. In 2010 the volumes of export of welding technologies grew as well by 25.5 % after recession in 2009. In 2010 Germany exported welding machines and devices at the cost of 1.4 bln Euro (+13.9 % to the values of 2009). Some growth of sales is observed at the market of welding technologies in the countries of Northern Europe, the Netherlands and Great Britain [11].

According to the assessments of Lincoln Electric the volumes of sales in the countries of South Europe (Portugal, Italy, Spain) in the IV quarter of 2011 decreased and prospect of their growth in the I quarter of 2012 is not predicted which is connected with considerable recession of industrial production and growth of unemployment reaching 22 % [4].

Experts from the companies like Frost&Sullivan, ESAB, Lincoln Electric observe noticeable growth of sales at the market of welding technologies in Russia. According to the forecast of Frost&Sullivan the volume of sales at domestic market of this country will grow almost twice in 2017 as compared to 2010, i.e. from 445.4 to 941.2 mln USD. It should be noted that 80 % of welding equipment supplied to the Russian market is low cost group of products and market volume grow due to increasing import of welding technologies unlike growth of domestic products [12].

The market of welding technologies in North America started growing in July, 2009 after remarkable recession. Basing on the assessment of market dynamics in 2009, the experts predicted that level of sales of 2008 would be achieved only in 2013. However sales of large companies (annual volume of sales was 2.0–1.5 bln USD) like Lincoln Electric, ITW exceeded the level of 2008 already in 2010. In 2011 the smaller companies like Thermadyne (annual volume of sales is about 500 mln USD) reached also the level of sales of 2008. In 2011 the market of welding technologies of this region developed very dynamically. For example sales of Lincoln Electric occupying 50 % of the market of North America grew in that segment of the world market in 2011 by 29 % and reached 1.3 bln USD. According to the assessments of experts the average annual growth of market of welding technologies in the USA in the period of 2011–2015 would amount 6.4 % and volume of the market — 7.1 bln USD [13].

The market of welding technologies of Asian region continues active development. The volume of this region in 2010 at the world market of welding technologies grew by 11 % as compared to 2008 mainly due to the markets of China and India. Today China is the leading world producer and consumer of welding technologies. According to the data of Frost&Sullivan the volume of market of equipment for welding and cutting in China in 2010 reached 3.5 bln USD among which 1.1 bln (about 28 %) covers inverter power sources for welding and cutting. The volume of production of inverter power sources is still negligible — it amounts approximately 60–70 % of the level of developed countries. According to the assessment of Chinese experts the share of inverter power sources in 2010 was about 47 % of all equipment being manufactured, while in 2012 it should increase up to 63 %. Moreover, in 2012 the cost of welding equipment products should exceed 4.2 bln USD [14].

The leading manufacturers of goods observe considerable growth of sales at the market of welding technologies in the countries of South America (Brazil,

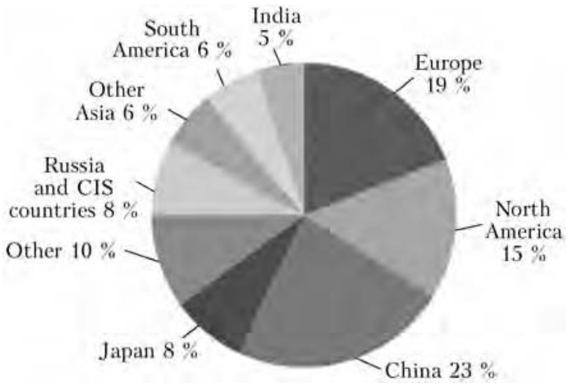

Figure 3. World market of welding technologies (distribution on regions in 2010)

Venezuela and Argentina). The sales of Lincoln Electric increased in that region by 33 % (up to 157 mln USD) in 2011, the market of welding technologies in the countries of North and South Africa.

The regional distribution of the world market of welding technologies is given in Figure 3. According to the assessment of ESAB specialists the cost value of the world market of welding technologies except of the market of welding robots and means of automation amounted 13.6 bln USD in 2010 [15].

In 2009–2011 the process of regional redistribution of industrial capacities on production of welding technologies of the large transnational companies continued. The investments into the building of new enterprises and purchase of existing ones became regular among the leading world companies-producers of welding technologies in India, China, South America, Eastern Europe and Middle East, facilitating growth, modernization and concentration of industrial capacities in those regions. For example in 2010 ESAB acquired 60 % of shares of Condor Equipamentos Industriais Ltd. leading Brazilian company, producing equipment for gas welding and cutting, and in 2011 — Sychevsky Electrode Plant (Smolensk region), occupying leading position at the market of welding consumables of Russia. Lincoln Electric invested 20 mln USD into development of capacities on production of welding consumables in Chennai (China). The industrial capacity of enterprise grew from 10–15 to 70 thou t of welding consumables per year. Lincoln Electric purchased also 100 % of shares of Chinese company Jinzhhou Jin Tai Welding and Metal Co., producing welding wire. In 2011 Lincoln Electric purchased two enterprises producing welding wire in Russia — Severstal-metiz Ltd. and OJSC Mezhgosmetiz-Mtsensk [1, 4].

The economic crisis gave also an impetus to diversification of activity of number of companies. For example, in November, 2011 it was announced about acquisition of the company Charter International plc. comprising ESAB, British Colfax Corporation, world leader in development, designing, production, sales and service of systems for transportation of liquids [16].

The process of widening (merge) of enterprises producing welding technologies was noticeably activated. It is especially active in China, India and countries of South-Eastern Asia where volume of small and medium business is very high. In September, 2011 Thermadyne announced amalgamation of its enterprises producing of welding technologies in Malaysia and China, and also enterprises producing equipment for plasma cutting in North America. Lincoln Electric amalgamated two enterprises which are located in USA and Canada [3, 4].

From the estimation made by specialists of Boston Strategies International, according to the Herfindahl-Hirschman index of production concentration, the market of welding equipment at the present period is estimated as moderately concentrated having the index 1281 in the IV quarter of 2009. From the forecast the index of concentration 1400 in the IV quarter of 2012 will exceed the level of 1400. This concentration index has already caused anxiety and is regarded as some prevention signal indicating the high probability of market monopolization [17].

As is seen from abovementioned, the period of 2008–2011 was rather complicated for manufacturers of welding equipment. The very quick change in tendencies at the market required adequate reaction from the manufacturers of goods in the sphere of production and management. As the manager of the largest Japanese Kobe Steel Ltd. company noted, the quick feedback on the demands of consumers allows reaching success today. The slogan of the company — Quality product/Technical support/Quick delivery is the formula of success at the present market of the welding equipment [18].

In accordance to the data of investigation carried out by the marketing company BCC Research (USA), the world market of welded products in 2011 was 16.3 bln USD (Figure 4).

It is expected that in 2012 the world welding market will reach 17 and in 2017 — 22 bln USD. The annual rate of growth of market up to 2017 will be 5.2 %. Here, the cost volume of market of welding consumables, shielding gas and protection means will reach 10.9 bln USD in 2012 and will increase to 14.4 bln USD by 2017. Annual growth of this market segment will amount on average 5.7 %; market of welding equipment was 4.5 bln USD in 2011. According to the forecast of BCC Research, its volume will increase up to 4.7 mln USD in 2012, and up to 5.5 mln USD and more by 2017. Annual growth of this market segment will amount on average 3.3 % [19]. The main branches-consumers of welding equipment are construction, transport, power engineering (including oil-and-gas production industry, electric power engineering, petro-chemical industry, production of pipes and construction of pipelines), repair and restoration works. Figure 5 presents average world

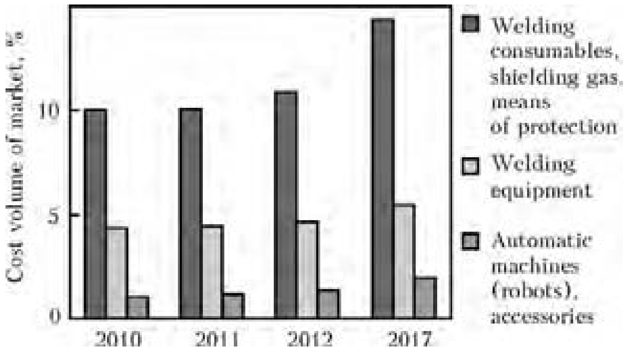

Figure 4. Estimation and forecast of development of the world welding market in 2010–2017

values of distribution of welding equipment market between main branches-consumers [10].

Unlike most metal processing branches of industry, having reduced their production, and respectively consumption of welding equipment in the period of crisis of 2008–2009, such branches as electric-power engineering (wind, nuclear, hydro and solar energy, construction of pipelines) and repair/technical maintenance increased the consumption of welding equipment and consumables.

From the assessment of experts of Frost&Sullui-van, the annual growth of market of welding equipment by 7 % is expected by 2015. It is predicted that volume of the market of welding technologies in this field of industry will grow from 1.9 (2008) to 3.0 bln USD (2015) [20]. From the assessment of experts of EASB and Frost&Sullivan the most prospective segment of the market of welding technologies is wind power engineering. Nowadays the volume of the world power production using wind power installations exceeds less than 2 %. However the tempo of growth of capacities is constantly increasing. Thus, the capacity of wind power engineering in the world in 2007 was 27,000 MW and in 2012 it is predicted to increase up to 60,000 MW. The investments into welding equipment of this market segment are constantly growing. From the estimates of ESAB specialists each new introduced 1 MW of capacity consumes 700 kg of welding consumables and 600 kg of welding flux. This market segment has good prospects for the further growth [1]. However in this case there are also more prudent estimates as for development of the market of wind power engineering. The President of ITW company considers that it is not necessary to expect too much benefit from wind power engineering, the rapid growth of the market can occur to be only a splash [2].

In spite of the accident at the Japanese NPS and protesting spirits concerning the development of nuclear power engineering in Europe and North America (USA) in 2012 the construction of two NPSs in South Carolina and Georgia will start. The Saudi Arabia is planning to construct 16 nuclear reactors over the next twenty years. Realization of this and some other projects gives grounds on a good prospect of growth of welding equipment sales in this market segment.

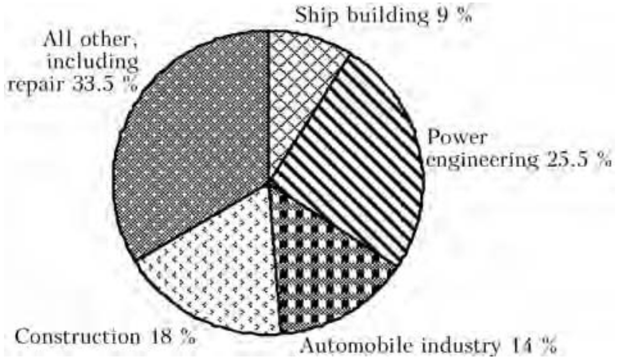

Figure 5. World market of welding technologies (distribution on the main branches of industry in 2010)

The growth in construction of new main on-land and underwater transnational and transcontinental oil-and-gas-pipelines in most regions of the world predetermined the increase in demand on welding equipment in this market segment. Many companies, for example Lincoln Electric, concentrate their efforts on the development of new types of welding equipment for orbital welding, as well as welding consumables for welding of spirally-welded pipes. From the results of studies of Frost&Sullivan, the world market of welding equipment will grow in this segment in the period from 2009 to 2016 by 45 % and reach 547.7 mln USD [21]. Good prospects of growth at the market of welding equipment and services are predicted by researchers in the sector of repair and technical maintenance [22].

Welding/brazing and surface strengthening (surfacing), as well as different types of thermal spraying (plasma, gas-flame, arc, high-speed gas-flame) are the main technologies among those which are used in the sector of repair and technical maintenance. The share of market of welding equipment and consumables in 2010, as well as forecast for 2017 in the sector of repair and technical maintenance are given in Figure 6.

From the data of investigations carried out by Frost &Sullivan, the cost volume of the world market of welding equipment for repair and technical maintenance was 650.3 mln USD in 2010. Specialists predict that in 2017 the market volume will reach 859.6 mln USD, and its mid-annual increment will be 4 %.

The equipment for arc welding occupies dominating position at the market of repair and technical maintenance. Its share in 2010 was 82.5 %, the share

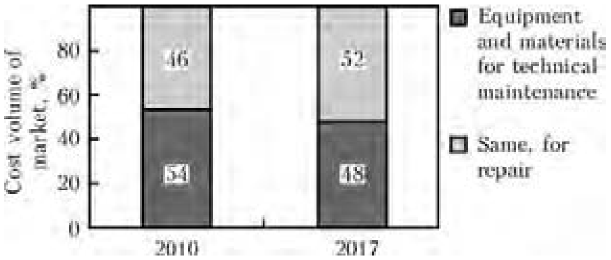

Figure 6. Structure of the market of welding equipment in the sectors of repair and technical service in 2010 and 2017 (forecast)

of equipment for gas welding — 15.8 %, other — 1.7 %. During the period by 2017 the share of equipment of arc welding will grow up to 84.8 %, while the equipment for gas welding will reduce down to 12.8 % in the structure of the market.

The cost volume of the world market of welding consumables for repair and technical maintenance amounted 1755.6 mln USD in 2010. Over the period of 2010–2017 the annual growth of market by 4 % is expected, moreover it is predicted that cost volume of the market in 2017 will reach 2450 mln USD, i.e. the market of welding equipment for repair and technical maintenance will exceed 3 bln USD in 2017.

Thus in spite of periodic recession during economic crises the world welding market continued its growth, development and transformation.

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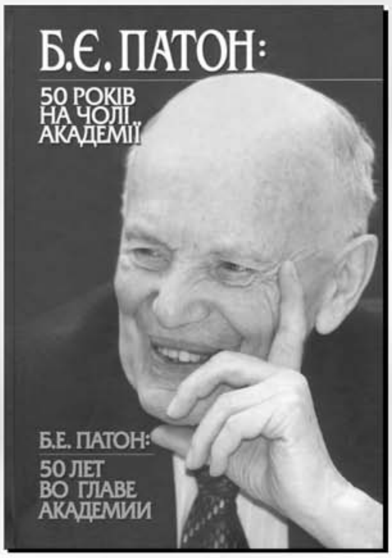
NEW BOOK

(2012) **B.E. Paton: 50 years at the head of the Academy.** — Kyiv: Akademperiodyka, 2012. — 776 p., 136 p. ill. (in Ukr. and Rus.).



The book highlights 50 year of activity of academician Boris E. Paton, outstanding Ukrainian scientist and research organizer, in the position of President of the National Academy of Sciences. Well-known scientists, including academicians A.P. Aleksandrov, G.I. Marchuk, Yu.S. Osipov, N.M. Amosov, Zh.I. Alfyorov, N.V. Bagrov, O.M. Belotserkovsky, P.A. Vityaz, D.M. Grodzinsky, L.V. Gubersky, I.M. Dzyuba, M.Z. Zgurovsky, E.N. Kablov, V.G. Kadyshevsky, N.N. Kudryavtsev, Yu.I. Kundiev, N.P. Laverev, N.V. Novikov, B.I. Olejnik, V.V. Panasyuk, Yu.N. Pakhomov, E.M. Primakov, V.A. Sadovnichy, A.M. Serdyuk, K.M. Sytnik, V.V. Skorokhod, A.A. Sozinov, V.I. Starostenko, B.S. Stogny, V.Ya. Tatsy and P.P. Tolochko share their impressions from their personal communication with B.E. Paton, his great influence on development of science and engineering. The book is illustrated with numerous photos.

It can be useful to all who are interested in the history of science.

Memorable dates

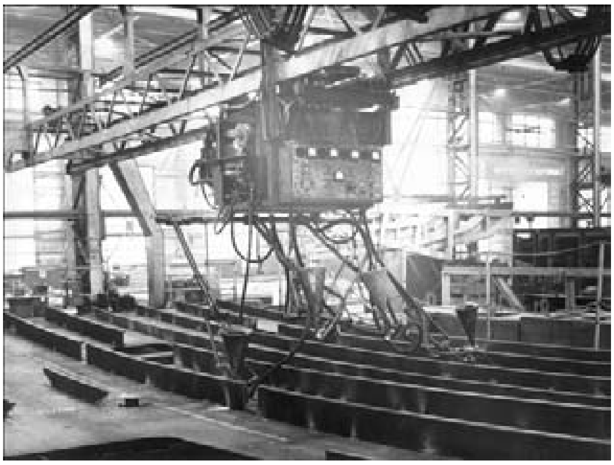
60 years ago USSR reached the point of mass introduction of automatic submerged-arc welding into industry. The Paton Welding Institute developed the technologies of combined assembly and welding, appropriate automatic machines and flow lines, rational welded structures for mining and power generation equipment, metallurgical furnaces and bridges

PWI CONTRIBUTION TO POST-WAR REVIVAL OF INDUSTRY

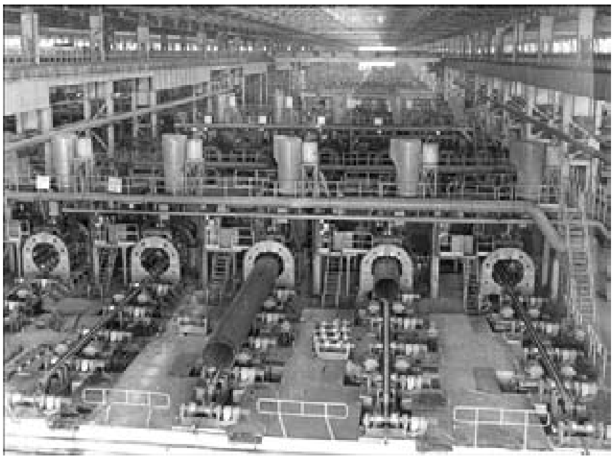
During the years of the Second World War in Ukraine, the whole territory of which was occupied by the German-fascist army, more than 16 thou industrial enterprises, mines, and bridges, and 200 thou industrial buildings were destroyed. Rehabilitation of the economy largely depended on welding production capabilities. Technological arsenal actually included versatile manual arc and gas welding processes. Automatic submerged-arc welding and resistance welding were adapted to mass production only in the shop. In some cases, particularly for critical structures, riveting was still applied. On June 9, 1947, the USSR Soviet of Ministers issued a decree on «Widening the application of automatic electric submerged-arc welding in industry», according to which it was planned in the next year and a half to put into operation 670 automatic welding machines in 111 plants of the country; markedly increase the scope of welding introduction in construction-and-assembly operations. The program on revival of industrial potential of the country, including also the industry of Ukraine, involved all the aspects of welders' activity: improvement of weldments, development of new welding consumables, machines and power sources, development of welding technique; promotion of science and education. The draft of the decree was prepared under the guidance of Evgeny O. Paton, who strived to widen the scope of automatic welding application, achieved during the war years in arms production. Submerged-arc welding began to be intensively developed in several directions.

Rationalizing welded structures was one of the most important directions, to which E.O. Paton gave his attention from the first day he became involved in welding fabrication. By improving the geometry, the Institute solved the problems of adaptability of welded structures to fabrication, lowering their weight, reducing the number of connectors. Conversion of achievements of the war years consisted in a fundamentally new approach to design and manufacture of machines, tanks, pipes and industrial facilities. At the same time, one of the important directions of welding fabrication development was designing versatile welding (tractors and hose semi-automatic machines) and specialized equipment for mass production of one type of products. In order to expand the field of submerged-arc welding application to construction-and-assembly operations, the problem of automatic arc welding of welds on a vertical plane with application of a mobile shoe with forced cooling was solved (G.Z. Voloshkevich).

Mounting tanks of 10,000 m^3 capacity from coiled structures



Mechanized submerged-arc welding of decking elements in Nikolaev Plant «Okean»



Automatic welding line in Khartsyzsk Pipe Plant

Country's leadership planned to rebuild first of all the mines and ore processing works. Donbass, Krivorozhie and a number of other regions needed thousands of wagons, mine risers and miner's lamps. However, Toretsky Machine-Building Plant produced just 4 wagons per shift, and here 25 parts had to be manually welded by short welds. Under the guidance of E.O. Paton, a new wagon design and new process of their production were developed, reducing the number of welds to 8. Flow line organization was based on the principle of combining the operations of assembly and welding of components with application of rolling-welding machines (R.I. Lashkevich, V.E. Paton, A.I. Korennoj). Nine welding heads ensured production of more than 60 wagons per shift. Designs of miner's lamps, and steel support risers were also improved, and special machines and automatic lines for their production were developed. By 1950 all the 220 main mines of the Donbass region were restored, several new mines were put into operation and coal production surpassed the pre-war level.

In 1946–1948 a line for manufacture of railway tank cars was put into operation at Illyich Plant in Mariupol. The inner and outer longitudinal and outer circumferential welds were made by automatic submerged-arc welding with welding tractors. Technology of continuous assembly and welding of locomobile boilers was introduced in 1950 at G.I. Petrovsky Machine-Building Plant in Kherson. At «Zaporozhstal» Plant automatic welding of vertical and horizontal welds of a blast furnace jacket of 1050 m^3 volume was implemented for the first time in the world (G.Z. Voloshkevich). New engineering solutions allowed shortening the time of blast furnace construction and improving their quality. The volume of mechanized welding was equal to 70 %. By the end of 1952, 23 blast furnaces of the capacity of 8.3 mln t of cast iron per year, 51 open-hearth furnace with annual capacity of 4.7 mln t of steel, and rolling mills of the capacity of 4.4 mln t of rolled stock were rebuilt and constructed.

E.O. Paton also emphasized the need to speed up the work on introduction of semi-automatic submerged-arc welding started by B.E. Paton as far back as in 1943. By 1948 the equipment and technology of submerged-arc welding with thin electrode wire (1–3 mm diameter) — hose-type semi-automatic arc welding was developed (B.E. Paton, D.A. Dudko, P.G. Grebelnik, I.N. Rublevsky, etc.), which allowed mechanization of production of such complicated structures with a multitude of short welds, as ship hulls.

In Ukraine PWI developed world's first method of joining thick metal in one pass — electroslag welding (B.E. Paton, G.Z. Voloshkevich), and position flash-butt welding of butt joints of pipes and railway rails (N.G. Ostapenko, V.K. Lebedev). An example of all-purpose application of automatic submerged-arc welding is construction of all-welded E.O. Paton bridge across the Dnieper (Kiev), which was completed in 1953, and was recognized by AWS to be an outstanding welded structure.

G.V. Raevsky managed to solve the most complicated task posed by E.O. Paton — rational fabrication of large-sized structures in the shops with application of automatic welding. The method of industrial production of tanks from flat panels was developed for the first time in the world. Three main elements of the tank (bottom, wall and roof) were assembled and submerged-arc welded by automatic machines into panels in the shop. For transportation they were welded into coils of suitable size, and then deployed in installation site. In site it remained to weld the closing vertical butt joints and weld the bottom and cover to the wall. Application of the new technology of tank manufacturing enabled four times reduction of labour consumption of erection work, and five to ten times shortening of construction time. In 1948 shops were constructed in the Kujbyshev (RF) and Zaporozhie (Ukraine) Plants of Metal Structures for industrial production of tanks. Mounting of 144 tanks (annual output) in the shortest terms provided the required number of oil storages for the country with annual saving of 7 mln roubles. This idea was useful in solving one more problem — fabrication of water-, gas- and product pipelines from two coiled strips up to 1–2 km long in one section, welded to each other along the long edges and coiled in the plants, and then deployed and expanded by air pressure in site.

Introduction of submerged-arc welding allowed moving more than 30,000 qualified workers to other jobs. Developments performed by PWI and their application during the first postwar years allowed successful rehabilitation of destroyed industry of the country. By 1952 the fuel-energy and metallurgical industry was completely restored in Ukraine.

Dr. (History) A.N. Kornienko, PWI

INTERNATIONAL CONFERENCE «Ti-2012 in CIS»

The traditional Annual International Conference «Ti-2012 in CIS» organized by the Interstate Association «Titan» took place in Kazan (Russia) in April 22–25, 2012. Nearly 200 visitors from Russia, Ukraine, Kazakhstan, Tajikistan, Japan, Germany, Italy, Norway, Luxemburg, Poland, Switzerland and China participated in the Conference. The scientists and specialists in the field of titanium from leading research organizations and industrial enterprises of Russia, Ukraine and other countries, such as Central R&D Institute of Structural Materials «Prometey», B.N. Eltsin Urals State Technical University, K.E. Tsiolkovsky Russian State University of Technology — MATI, All-Russian Institute of Light Alloys, All-Russian Institute of Aircraft Materials, Institute of Problems of Superplasticity of Materials of the RAS, Institute of Structural Macrokinetics and Problems of Materials Science of the RAS, Corporation VSMPO-AVISMA, A.M. Gorky Zelenodolsky Zavod, OJSC RITM, OJSC «Chepetsky Mekhanichesky Zavod», OJSC Normal, OJSC Elektromekhanika, E.O. Paton Electric Welding Institute of NASU, G.V. Kurdyumov Institute for Metal Physics of NASU, H.V.Karpenko Physical-Mechanical Institute of NASU, Donetsk O.A. Galkin Institute of Physics and Engineering of NASU, State R&D Institute of Titanium, State Enterprise «Antonov», ALD Vacuum Technologies GmbH (Germany), TiRus International SA (Switzerland), NTC for Titanium Inc. (Japan), etc. delivered their reports at the Conference. In general 88 reports were presented at the plenary meetings and in the sessions «Raw materials. Metallurgy», «Metals science and technology of titanium alloys» and «Economy of titanium».

The delegation of specialists of «Prometey», one of the leading world centers in the field of materials science of titanium alloys, presented a large number of reports on development of new and modernization of existing titanium alloys, determination of their service characteristics including long-term ones, development of technologies for their welding, deformation and heat treatment. In the work of the Conference the scientists of two largest materials science centers in Russia: Urals State Technical University and MATI, where intense investigations in the field of materials science of titanium and alloys on its base are carried out, took an active part.

The scientific and technical developments of the institutes of the National Academy of Sciences of Ukraine in the field of materials science of titanium

alloys were fully enough presented at the Conference. From the E.O. Paton Electric Welding Institute the reports on weldability of new heat-resistant and structural titanium alloys, kinetics of absorption of nitrogen by liquid titanium, innovative technological developments of argon-arc and electron beam welding of titanium alloys, production of large-size discs for gas-turbine machines of heat-resistant titanium alloys, produced using methods of electron beam melting, were delivered. The specialists of the G.V. Kurdyumov Institute for Metal Physics described materials science, physical-chemical and technological aspects of manufacture of semi-products of the parts of titanium alloys including application of methods of powdered metallurgy. The representatives of H.V. Karpenko Physico-Mechanical Institute presented their developments in the field of deposition of gradient coatings on the workpieces of titanium alloys, and specialists of Donetsk O.A. Galkin Institute of Physics and Engineering showed possibilities of improvement of mechanical characteristics of titanium using methods of spiral extrusion.

In the reports of D.A. Kurochkin (VSMPO-AVISMA), T. Masahiro (Japanese Titanium Association), S. Hancock (TiRus Int. SA), T. Nishimura (NTC Corp. for Titanium) and I.S. Polkin (VILS) it was stated about the growth of volumes of orders on titanium products in 2011 both in civil as well as in military sectors of industry. Thus, for example, the world volume of production of titanium rolled metal in 2011 grew by 24 % as compared to 2010 and amounted to 140 000 t. The main consumers of titanium semi-products keep remaining military and civil aircraft building, enterprises-manufacturers of heat-exchangers and chemical devices. The application of titanium in oil-and gas production industry, medicine, production of sport goods is growing.

After the meetings the participants of the Conference visited A.M. Gorky Zelenodolsky Zavod (Tatarstan, RF), studied some types of production for assembly of ship hulls and the world largest shop for casting titanium and participated in the ceremonies on the occasion of producing the million casting since putting into operation of the production in the late 1960s. The shop for casting titanium is equipped with nine vacuum-arc casting furnaces and can produce up to 700 t of cast billets per year. At its area the world largest vacuum-arc furnace «Neva-5» is located, which can produce castings of titanium alloys of up to 4000 kg mass.

In conclusion one should mention about the high level of the Conference organization and express gratitude to its organizers in the person of Interstate Organization «Titan» and A.V. Aleksandrov, its chairman.

Prof. S.V. Akhonin, PWI

NEWS

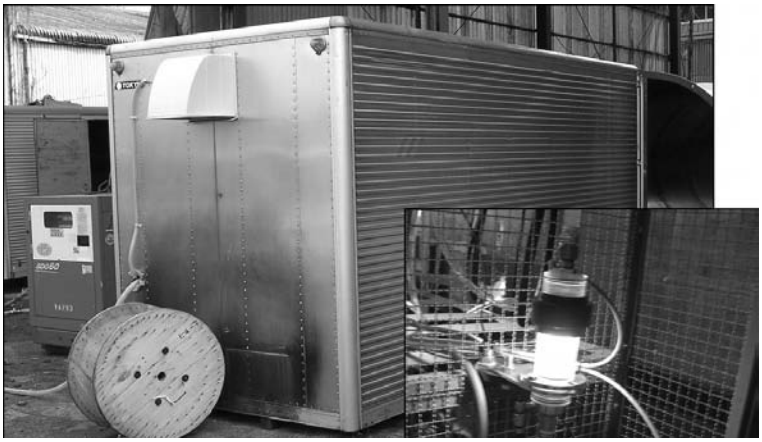
PLASMA TREATMENT OF CONTAMINATED WATER

Mobile complex for plasma treatment of water with radioactive contamination was developed and manufactured on the basis of Japanese company «Kanazawa» at participation of Kiev companies LIKOM and Representative Firm «Institute of Gas» from Ukrainian side and «Ohmi Industrial Engineering» from Japanese side.

Public tests of the process of plasma treatment of radioactive water in two stages were carried out using indicated complex. Representatives of electrogenerating company «Tokyo Electric Power», representatives of prefecture, scientists, journalists and interested companies participated in them.

The first stage of tests was carried out in Date city (Fukushima Prefecture) on February 28, 2012 and the second took place in Kamagaya (Chibo Prefecture) on March 08, 2012.

The experiments proved that application of plasma in technology of water decontamination is perspective for industrial application and has a series of advantages, i.e. absence of formation of by-products and high efficiency. Location of units for plasma chemical treatment of radioactive water requires no special areas. Besides, they can be used for cleaning and decontamination of sewages of various origin in stationary and mobile variants. Expenses for water treatment do not exceed the expenses in comparison with traditional methods.



General view of mobile plasma unit for treatment of radioactive water

Positions of analysis	Results of analysis, Bq/kg	
	Contaminated water	Treated water
Iodine-131	Not found	Not found
Cesium-134	7400	110
Cesium-137	11000	160
Place of diversion: Date city (Fukushima Pref.). Date of diversion: 27.02.2012; time of diversion: 10:30 (contaminated water), 14:30 (treated water).		

Developed at PWI

TECHNOLOGY AND EQUIPMENT FOR PRODUCTION OF LARGE PROFILED SINGLE CRYSTALS OF REFRACTORY METALS

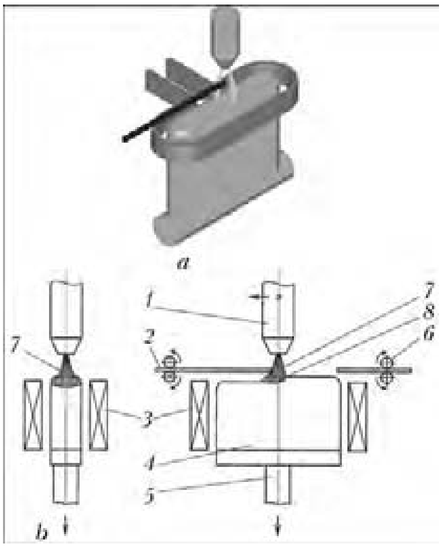


Figure 1. Flow diagram of the process (*a*) and equipment (*b*) for plasma-induction growing of single crystals: *1* — plasmatron; *2* — rod; *4* — single crystal; *5* — mould bed; *6* — rod feeding mechanism; *7* — metal droplet; *8* — metal pool

Plasma-induction floating-zone technology and equipment are available to produce tungsten and molybdenum single-crystal ingots measuring 20 × 140 × 170 mm or more (Figures 1 and 2). The productivity of the equipment for melting single crystals is 0.5 kg/h.

Single crystals of refractory metals, including tungsten and molybdenum, were usually commercially produced in the form of up to 30 mm diameter rods. However, currently the demand is for single crystals of a larger diameter to produce sputtering targets with a diameter of not less than 60 mm to be applied in electronics, anodes for high-power X-ray tubes, mirrors for industrial lasers, and boats and containers to grow large single crystals of oxides and salts, as well as for wide-area single-crystal rolled products.

Large oriented single crystals of refractory metals, and profiled ones in particular, are in much the same demand as large ingots of steel, titanium and other metals and alloys. Single crystals of refractory metals are high-tech products, and the majority of programs in nuclear space power generation and aerospace engineering critically depend on breaks-through in R&D in the field of high-temperature materials.

For a number of years the problem of growth of large single crystals of refractory metals seemed unsolvable because of their high melting temperatures. And only the method of plasma-induction floating-zone growth of single crystals made it possible to solve this problem in principle.

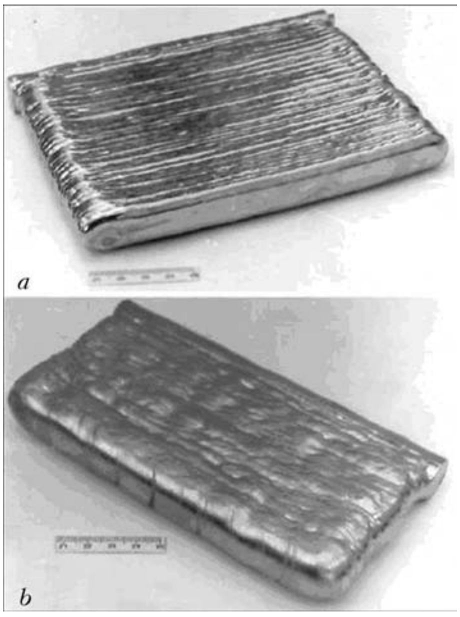


Figure 3. Tungsten (*a*) and molybdenum (*b*) single crystal

Uniqueness of this method is that it has almost no limitations, both in size and profile of cross section of crystals (circle, square, plate, tube etc.). The combination of plasma and induction heating allows maintaining the molten metal pool in the electromagnetic field without any contact with a copper being cooled. It is this fact that determined a high potential of this method for growing of large single crystals of refractory metals, as increase in size of the single crystals of refractory metals has a decisive effect on widening of the scales of their application in engineering. Oriented single crystals of tungsten and molybdenum, and the profiled ones in particular, can serve as ideal billets for production of wide-area rolled products of refractory metals (Figure 3).

Figure 2. Plasma-induction instalation

Application field. Single crystals are mainly applied as a material for research and manufacture of special products, most often for defence, space and other high-tech engineering facilities. Also, single crystals are used as targets for sputtering units, in X-ray and laser equipment, and in metallurgy.

UNITS FOR PULSE-PLASMA SURFACE HARDENING OF MACHINE PARTS AND TOOLS

Figure 1. Pulse plasmatron for surface hardening treatment

Figure 3. General view of the unit for pulse plasma hardening treatment of surfaces of parts, including for thermal spraying of coatings

An efficient method for increasing energy density is detonation of fuel gas mixture in a reaction chamber of plasmatron (Figure 1), where the electric field is induced. Flowing of the electric current through the front of the detonation wave leads to heating and acceleration of the combustion products. A pulse plasma jet with a velocity of up to 8 km/s and temperature of up to 20,000 K forms at the plasmatron exit. The plasmatron provides not only a wide-range control of the pulse energy density, but also addition of various alloying elements (W, Mo, Cr, Ti, V, Al, Cu, Ni, C etc.) to the plasma. This ensures formation of a layer of new high-quality materials and coatings on the workpiece surfaces (Figure 2).

The key advantages of the pulse plasmatron include:

- high energy density within the treatment zone and possibility of its smooth adjustment;
- short-time and local effect limiting the heat-affected zone;
- simplicity of generation of pulse plasma jets and possibility of treating complex surfaces by the contactless method;
- possibility of automation of the treatment process;
- possibility of performing high-energy thermal spraying of coatings;
- treatment of the working surfaces of tools and parts with the pulse plasma jet provides their high wear, heat and score resistance, combined with high strength of a part.

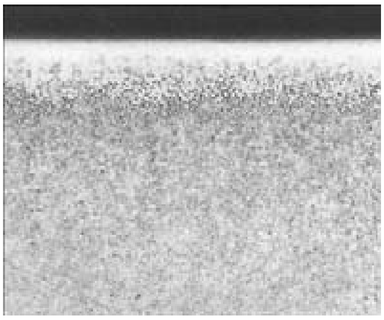


Figure 2. Appearance of a layer of nanocrystalline material on the carbon steel surface after hardening treatment

Units for pulse plasma treatment of the «Impuls» series are characterised by versatility and flexibility (Figure 3). They can be used to improve wear, corrosion and heat resistance, antifriction properties and erosion resistance of parts of different configuration and weight. The technology can be applied to change properties of surfaces of the new parts and repair the worn-out parts.

Compared with similar high-energy equipment (e.g. lasers), the «Impuls» series units are characterised by simplicity of operation, low cost and high efficiency of utilisation of the electric energy.

The pulse plasma technologies are efficient for hardening of tools and machine parts used in almost all industrial sectors (Figure 4):

Figure 4. Pulse plasma hardened tools applied in different industrial sectors

- metallurgy (for deposition of heat-resistant coatings, hardening of cutting tools and forming rolls);
- aircraft engineering (for deposition of coatings on light alloy parts);
- agriculture (hardening of tools, e.g. beet cutters and agricultural machine parts);
- railway transport (hardening of machine parts and repair of shafts);
- machine building (hardening of metal working and metal cutting tools, deposition of coatings on components of hydraulic actuators);
- mining (deposition of corrosion- and acid-resistant coatings);
- woodworking (hardening of tools);
- textile industry (modification of surfaces of textile machine parts);
- food industry (hardening of beet, paper and wrapping film cutters).

Many years' industrial tests and experience of application of the technology show that performance of the parts after pulse plasma treatment increases 2–6 times.

The pulse plasma technology is applied to harden the following parts:

- metal cutting tools (machine building);
- components of dies and fixtures (hardware industry);
- tools for metallurgical industry (rollers, knives, saws);
- tools for woodworking, printing and light industries;
- machine parts and mechanisms (motor car construction, aircraft engineering, engine construction etc.).

The plasma jet is formed by compressing the detonation wave with the electric current. Supply voltage of the plasmatron is 3000 V. The parts are treated in air atmosphere at frequencies of up to 4 Hz.

The technology provides the treatment productivity equal to 300 mm^2/s at installed power of 20 kW. The flow rates of gases are as follows, m^3/h: oxygen — 1, fuel gas — 0.2, and air — 4.

The increase in performance after hardening is as follows:

- 3–4 times for knives and millers;
- 5–6 times for steel saws;
- 1.5–2 times for saws of hard tungsten-cobalt alloys;
- 3–6 times for die blocks and punches;
- 3–5 times for machine parts.

Materials being hardened:

- iron-base alloys;
- titanium-base alloys;
- hard alloys based on tungsten carbides;
- powder alloys.

The «Impuls-3/4» unit is made on the base of a standard machine tool for machining of parts (milling machine tool, lathe) and/or welding manipulator.

The «Impuls-5» unit is equipped with a three-axis manipulator or robot to move the pulse plasmatron.

The UN-138M unit is a specialised facility. It is fitted with a noise-protecting system and versatile semiautomatic manipulator. The unit serves to harden cylindrical parts and deposit coatings under workshop conditions.

The mobile MOPUS unit is mounted in a body of movable motor shop KM 131 based on cross-country vehicle ZIL 130. It serves for hardening of parts under field conditions, e.g. woodworking tools and sugar beet cutters.

The cost of hardening is no more than 10 % of the cost of a part, and in a case of hardening of expensive tools it is 2–3 % of their costs. As a rule, the pay-back period is less than 3 months at full utilisation of the «Impuls» series units.

The most successful example of application of this technology is a work section arranged at the Cherepovets steel rolling plant for pulse plasma hardening of tools.

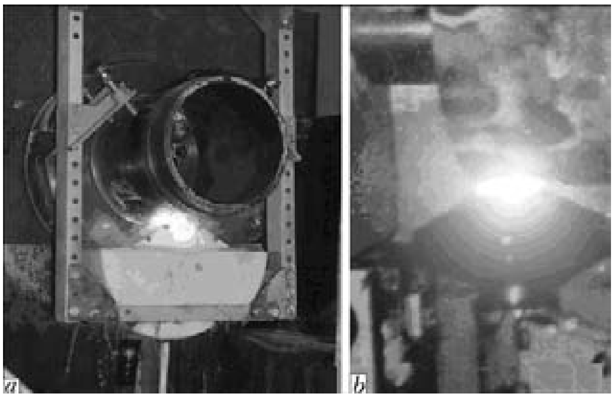
ELECTROLYTIC PLASMA THERMAL-CYCLING TREATMENT

Thermal cycling surface treatment is performed with the electric current, which is switched by electrolyte (alkaline water solution). Alloying elements (metal ions) are added to the electrolyte and thus participate in the diffusion process of alloying the heated surface of a workpiece. The surface is cooled by the electrolyte and due to heat capacity of the workpiece. Cycling of the heating and solidification process accelerates diffusion and provides formation of the surface layer with a microcrystalline structure.

The unit comprises ingenious electrolytic-plasma devices (Figure). They operate on the basis of using liquid electrode, i.e. electrolyte, formation of the plasma layer on the workpiece surface, and release of energy in this layer in the form of electric discharges. This allows implementing thermal cycling heating, alloying and structuring of the surfaces of metal parts to a depth of 0.1–10 mm.

The technology is power saving and environmentally clean. The power utilisation factor is 80–90 %.

Automation of the technology and thermal cycling of the workpiece surfaces within the preset temperature ranges are provided by using the contactless temperature sensor and control systems.



Types of devices for hardening cylindrical parts: *a* — attached to workpiece; *b* — fixed on manipulator

The technology is efficient both for protection of the workpiece surfaces from abrasive wear and for formation of the hardened layer on parts of the type of hydraulic rods, forming and mill rollers.

The technology is efficient for mining engineering, metallurgical industry, agricultural machinery and woodworking.

The key advantage of the technology is a manifold power saving, as well as improvement of physical-mechanical properties of the surface layer and, hence, performance of metal parts operating under wear and heavy load conditions.

The technology is applied in industry for hardening treatment of surfaces of various parts: drill pipes (rods), large-size crankshafts, saws and knives. Performance of these parts increases 2–3 times, and power consumed for producing them decreases 3–5 times.

Novelty of the technology and equipment are covered by dozens of the USSR author’s certificates and Russian patents.

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