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

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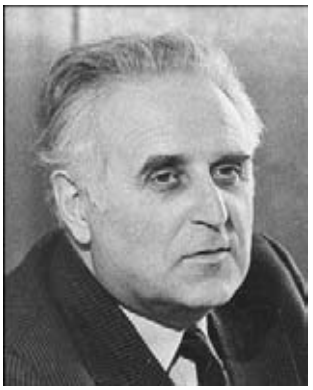

Rapid development of machine building, construction and other industries of the Soviet Union in the post-war years required elaboration and investigation of new consumables for welding of different grades of structural steels. Also, it was necessary to build new plants for industrial production of general-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

lines 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.