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Plenary Papers for International Conference on Welding and Related Technologies into the Third Millennium

GLORIOUS JUBILEE

Boris E. Paton is an outstanding Ukrainian scientist in the field of welding, metallurgy, technology of materials and materials science, prominent public figure and talented organiser of science, academician of the National Academy of Sciences of Ukraine and Russian Academy of Sciences, professor, honoured scientist and technologist of the Ukrainian SSR, Twice Hero of the Socialist Labour of the USSR, Hero of Ukraine, participant in the Great Patriotic War, and liquidator of accident at the Chernobyl NPP.

The international authority of B.E. Paton is a result of his versatile and extraordinarily fruitful scientific and engineering activity, and of his great effort to use results of the fundamental research for solving problems of the society.

For over 55 years B.E. Paton has been heading the internationally recognised research and technology centre — the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, and since 1962 he has been a permanent President of the Academy of Sciences of the Ukrainian SSR (now the National Academy of Sciences of Ukraine).

Boris Paton was born on the 27th of November 1918 in Kiev in the family of Evgeny Oskarovich Paton, professor of the Kiev Polytechnic Institute and well-known expert in the area of bridge construction. In those years Evgeny Paton chaired the bridge faculty. He was the author of original bridge designs and engineering structures, and was in charge of their construction. Being experienced in cooperation with many machine-building enterprises and participating in major construction projects, he was well aware of the strong dependence of progress in these industries upon utilisation of the new technology for materials joining — welding.

To make welding a reliable technological process, it was necessary to conduct comprehensive investigations into mechanics of welded structures, metallurgical processes, welding metal science and physics of the arc discharge, as well as develop welding equipment, consumables and new welding technologies. To address all these problems, the Electric Welding Institute was founded in 1934 by the initiative of E.O. Paton within the system of the Academy of Sciences of the Ukrainian SSR.

The intensive working activity of the Evgeny Paton absorbed in solving a large number of scientific, technical and organisational problems was witnessed by the son and, undoubtedly, affected formation of his character and attitude to work and people.

In 1941, Boris Paton graduated from the Kiev Polytechnic Institute and was assigned to the «Krasnoe Sormovo» plant in Gorky. In the following year he was appointed to the Electric Welding Institute, which was evacuated at that time to the Uralvagonzavod Plant in Nizhnij Tagil. It was that famous Plant where in 1942 B.E. Paton started his manufacturing and scientific activity. From then, for 11 years Boris Paton was working together with his father; those were the years of his growth as a scientific worker and researcher, and then a leader of a large scientific team.

Boris Paton proved to be one of the most talented students and a worthy successor of his father. He continued and brilliantly developed the work started by E.O. Paton.

During the war years the Institute focused all its efforts on helping the largest Ural Car Building Plant (Uralvagonzavod), and later — other plants that mastered the mass production of tanks. Along with a big and intensive work at defence factories, the team of the Institute continued the research efforts. In 1942, V.I. Dyatlov discovered the phenomenon of self-regulation of electrode melting in submerged-arc welding. Investigation of this phenomenon by B.E. Paton, together with A.M. Makara, P.I. Sevbo and M.N. Sidorenko, allowed the development of portable, simple and reliable automatic welding devices, and the application of the simplest AC power units. Each automatic device controlled even by an unskilled operator replaced the work of eight to ten experienced welders. Application of automatic welding devices under conditions of acute shortage of manpower solved the most important problem of defence production. All associates of the Institute headed by its Director took a direct part in assembling and setting up of welding equipment.

Tank T-34 manufactured on enormous scales by Uralvagonzavod and other factories of the country was recognised by experts to be the best medium-weight tank of the Second World War, and predetermined to a considerable degree our victory over fascism. Lives of many thousands of tank crews were saved thanks to the reliable welded armour. In 1943, B.E.Paton was awarded the Order of the Red Labour Banner for the achievements in mechanisation and automation of welding operations used for the fabrication of military equipment.

Regardless of the fact that in the war years Boris Paton was extremely busy working in welding shops of the Plant, he completed a number of important investigations into static properties of automatic equipment for submerged-arc welding. Further investigations in this field and their extension were the content of his thesis for a candidate of technical sciences degree, which Boris Paton defended in 1945. In his later studies, Boris Paton showed that the automatic equipment providing a constant wire feed speed, fitted with power sources and fast-acting voltage regulators, possessed the optimal characteristics. It was the conclusion that underlay the development of equipment for mechanised submerged-arc and gas-shielded welding. For the development of semi-automatic submerged-arc welding equipment, in 1950 B.E. Paton and his colleagues, and also experts of the «Elektrik» Plant in Leningrad, were awarded the Stalin Prize of the USSR in the field of science and technology. Later on, this principle of control was used as a basis for building semi-automatic devices for gas-shielded welding.

Boris Paton generalised results of systematic studies associated with the conditions of stable arcing and regulation of the arc. He successfully defended his theses for a doctor of technical sciences degree dedicated to this subject, and in 1951 was elected a Corresponding Member of the Academy of Sciences of the Ukrainian SSR. Investigations in the field of welding power units, and welding transformers in the first turn, were carried out under the leadership of B.E. Paton. Automatic submerged-arc welding was one of the most efficient processes in the 1950s. The industry needed new developments in the field. And the Institute deployed research on metallurgical processes of submerged-arc welding. Within a short period of time the fundamentals of the theory of metallurgy of submerged-arc welding and surfacing were worked out, and a wide range of different-application fluxes was developed. New technologies were elaborated for high-capacity production of fused fluxes.

The Khartsyzsky Pipe Plant was the first in the country to produce high-quality large-diameter pipes, based on the above developments. Boris Paton was one of the founders of this production. This work was pioneering and fundamental for arrangement of up-to-date mass production of large-diameter pipes at the Khartsyzsky, Chelyabinsky, Volzhsky, Vyksunsky and other factories for the construction of high-capacity gas transportation systems in the USSR. It became the lifetime work of Boris Paton.

In those years the Institute developed a new process for submerged-arc welding in different spatial positions. This method allowed mechanisation of welding operations at construction sites. For the first time the method was applied to erect span structures of the Kiev Bridge across the Dnieper River, which was called after Evgeny Paton — chief ideologist of welded bridge construction and technical supervisor of designing and building of this unique structure. Later on, another new method of flux-cored wire arc welding with forced weld formation was developed, which was widely applied for the construction of span structures of the Moskovsky and Yuzhny bridges across the Dnieper River in Kiev and across the Volga River in Saratov, construction of main pipelines, metallurgical facilities, chemical apparatuses, and ship hulls.

In 1950, Boris Paton was appointed to the post of Deputy Director of the Institute on scientific work, and in 1953, after the death of Evgeny O. Paton, he became the Director of the E.O. Paton Electric Welding Institute of the Academy of Sciences of the Ukrainian SSR. Further progress of welding science, technology and production required that a systematic and planned approach be used on the scales of the entire country. Boris Paton developed the planned arrangement of research efforts of the Institute. He established business contacts with heads of industrial enterprises, National Economy Councils, Ministries and State Planning Committee of the USSR, arranged and headed preparation of proposals for development of welding in the USSR. In June 1958, the Central Committee of the Communist Party of the Soviet Union and the Council of Ministers of the USSR issued resolution «On Further Industrial Application of Welding Engineering», which provided for the fundamental research to be conducted in the field of welding processes, development of equipment, materials and technologies, foundation of new research institutions and factory laboratories, construction of specialised facilities for production of welding equipment, consumables and welded structures. Owing to passing other similar resolutions during the five-year periods that followed, the USSR became the leading country of the world in the field of welding, and our American colleagues called Kiev the world capital of welders.

Boris Paton has an exceptional ability to interact with people. He is always ready to support an interesting idea and estimate a work done at its true value. His enthusiasm, unique capacity for work and consideration for every staff member create a good working atmosphere at the Institute.

An example is the development of electroslag welding. While developing a method for field welding, G.Z. Voloshkevich, an associate of the Institute, discovered that molten slag with the electric current flowing through it could be used as a heat source. The process was called the electroslag one. Boris Paton not only supported this process, but also predicted a great future for it. He managed to concentrate the efforts of the work team on solving the most important problems of electroslag welding. As a result, a new promising method for welding heavy sections of metal was developed within the short terms, which was verified under production conditions and made suitable for extensive application.

Application of electroslag welding radically changed the technology of production of such components as drums of pressure boilers, beds of heavy presses and rolling mills, wheels and shafts of hydraulic turbines, etc. Large-size cast and forged components were replaced by welded and welded-forged ones, which turned out to be much more cost effective.

In 1957, B.E. Paton and G.Z. Voloshkevich, together with workers of the Novokramatorsky Engineering Plant (Kramatorsk) and Krasnyi Kotelshchik Plant (Taganrog), were awarded the Lenin Prize for the development of the electroslag welding process and manufacture of large-size critical-application parts on its basis. This work was marked by the Grand Prix at the International Exhibition in Brussels in

1958. A number of companies from industrialised countries of the world bought licences for application of this high-productivity welding method.

In November 1958, Boris Paton was elected a Full Member of the Academy of Sciences of the Ukrainian SSR.

Boris Paton believes that arc welding will continue to be the main welding process in the foreseeable future. He is paying much attention to further improvement and development of this process, and guides the team of the Institute to addressing topical problems in this area.

Boris Paton initiated investigations into the processes of formation of welding fumes and development of a new generation of low-toxicity welding electrodes. High-capacity workshops and factories for production of electrodes were built. Wide application of this development made it possible to radically improve labour conditions and decrease many times the rates of occupational diseases of welders.

In the 1950s, the Institute started developing a new area — automation and mechanisation of the processes of hard-facing of working elements of mining machines and equipment with different materials to increase their wear resistance. Fundamental research was conducted to study the hard-facing processes by the submerged-arc, gas-shielded, self-shielding flux-cored wire and plasma jet methods. Unique surfacing equipment, consumables and technologies were developed. Commercial production of surfacing flux-cored wires was arranged. This area proved to be highly promising. The Institute is still active in it, and the technologies are widely applied in different industries.

In 1958, Boris Paton initiated development of new methods for mechanised welding of structures under field conditions, at erection sites, on building berths, and under the water, for which he suggested using flux-cored wire. Extensive research was carried out to study metallurgical and technological peculiarities of this welding method. Self-shielding and gas-shielded wires were developed for different applications, and production of flux-cored wires was arranged. Now this area is among the leading ones in the world welding science and technology.

Research and development efforts on the method of semi-automatic underwater flux-cored wire welding opened new possibilities for exploration of the continental shelf, construction and repair of port systems, pipeline transitions through rivers, and other facilities.

Results of many studies by Boris Paton and his colleagues in the area of arc welding were published in the monographs he edited: «Technology of Electric Fusion Welding of Metals and Alloys» (Moscow: Mashinostroenie, 1974), and «Microplasma Welding» (Kiev: Naukova Dumka, 1983).

Boris Paton contributed significantly to the development of flash butt welding. Pioneering investigations were completed to study the effect of short circuit resistance of flash butt welding machines on stability of melting and heating, and on weldability of metal. High efficiency of welding current feedback was proved. Ingenious designs of transformers were put forward, and theoretical principles for their calculations were elaborated. Systems for multifactor control of the flash butt welding process were developed for the first time in the world practice under the leadership and with the direct participation of B.E. Paton. Several generations of ingenious machines, which have been in operation for decades in many countries throughout the world, were built. Among them are rail welding machines, unique inside-pipe flash butt welding systems, machines for welding of rocket parts made from aluminium alloys, and many others.

Boris Paton became interested in using high-power electron beams for heating metal in welding as early as in the fifties. It turned out that application of the electron beam holds high promise for welding various thick-walled vessels made from steels, high-strength alloys based on aluminium and titanium, and other materials. Complicated problems of ensuring stability of the electron beam in the atmosphere of metal vapours were solved, special features of formation of narrow and deep welds were determined, and control methods providing reproducibility of optimal welding parameters were developed. All this allowed the manufacture of the advanced equipment and development of the advanced technologies, which received international recognition.

Tungsten-electrode arc welding over the layer of an activating flux-paste, which was later called A-TIG welding, was developed by the E.O. Paton Electric Welding Institute in the middle of the 1960s. Evaporation of the activating flux can provide contraction of the arc column, increase the penetration depth several times, raise the productivity of welding, and improve the weld shape. This ingenious technology gained acceptance in the USSR and then in the CIS countries. The Paton technology PATIG obtained recognition also in the so-called «far foreign» countries. Recently, Boris Paton has initiated research aimed at elaboration of theoretical fundamentals of the arc welding processes using activating fluxes. Main principles of the impact of arc contraction on characteristics of the heat and dynamic effects exerted on the weld pool were determined, and the mechanism of deep penetration of metal was explained.

At the end of the 1980s, B.E. Paton supervised the research efforts of the Electric Welding Institute to study hybrid (laser-arc and laser-plasma) processes of welding and treatment of materials. Designs of the direct- and indirect-action laser-arc plasma torches were offered, and different-application plasmatrons were built. New processes of hybrid laser-plasma welding and surfacing were developed, including the process of hybrid laser-microplasma welding of small thicknesses of metals.

In the 1960s, B.E. Paton headed the research efforts to study technologies for production of different coatings and composite materials by electron beam evaporation of components and condensation of vapours on surfaces of parts or special substrates. The electron beam technology for deposition of coatings, which found application in a number of engineering sectors, allows many times extension of service life of different parts, e.g. gas turbine blades.

The electron beam hybrid nanotechnology is capable of filling up a niche between the thin-film and traditional technologies for manufacture of materials and parts. The key feature of the new technology is the possibility of implementing solid-state synthesis of the preset sequence of structures, the combination of which is a new product.

In the eighties, the Electric Welding Institute was active in investigations into the methods of thermal spraying of coatings using gas-oxygen flame and arc plasma, which were initiated by B.E. Paton. Equipment and consumables were developed to provide protective layers with different properties.

As early as in the first half of the sixties B.E. Paton put forward an idea of using welding to assemble metal structures in the open space, which was strongly supported by S.P. Korolyov.

In 1969, welding in space around the Earth was implemented for the first time under the leadership of Boris Paton. Experiments on electron beam, plasma-arc and consumable electrode welding were carried out by cosmonaut V.N. Kubasov on board the «Soyuz-6» piloted spaceship. Peculiarities of weld formation under the zero gravity conditions were thus studied, and the possibility of producing tight and well formed welds in space was proved.

In 1979, the concept of depositing various metallic coatings on surfaces of the space station components and devices was successfully verified. Special device «Isparitel» was developed for this purpose, and the versatile hand tool (VHT) was built for welding, brazing and deposition of coatings. VHT was tested in the open space in 1984 by cosmonauts S.E. Savitskaya and V.A. Dzhanibekov. This experiment launched a package of systematic multipurpose investigations and experiments on optimisation of structural components and technology for installation of large orbital structures and facilities. In 1986, a structure in the form of a dismountable girder was constructed in space («Mayak» experiment). The first brazing of connections of truss structures was carried out in 1991, and the unit for opening and deployment of multiple-use solar cells was built on the «Mir» orbital station. Results of many years' research and development efforts in the field of space technologies were presented in monograph «Welding in Space and Related Technologies» by B.E. Paton and V.F. Lapchinsky, which was published in 1997 in Great Britain. Then these results were summarised in book «Space: Technologies, Materials, Structures» published in 2000 under the edition of B.E. Paton.

When assessing the contribution made by B.E. Paton to the development of the USSR space program, Yu.P. Semyonov, academician of the Russian Academy of Sciences and Chief Designer of rocket-space systems at RPC «Energiya», who had been working with S.P. Korolyov for many years, writes: «B.E. Paton belongs to the Grand Pleiad of Soviet scientists and designers, who made the USSR in the years of its existence a mighty and great power... He made an invaluable contribution to the science and practical application of welding. Thanks to him, we were the first in the world to develop the space technologies and conduct the first welding experiment in space... B.E. Paton is a prominent scientist of the 20th century. His distinctive and unique feature is to make a reality of ideas... He made a great contribution to rocket N1 (to explore the Moon)...He did much for spaceships «Soyuz» and «Progress». He supervised the efforts on building unique devices to realise the space technologies. Cosmonauts S.E. Savitskaya and V.A. Dzhanibekov were the first in the world to prove high performance of these devices and technologies in the extra-vehicular activity».

At the beginning of the 1970s the first samples of the systems using experimental-statistic models of welding processes were made under the leadership of B.E. Paton. Intensive development of these studies led to building of automatic control systems for welding processes, installations and mechanised lines using the microprocessor facilities.

A big package of fundamental and applied research was completed under the leadership of B.E. Paton in the field of static and cyclic strength of welded joints, their resistance to brittle and fatigue fractures, and performance under the low-temperature conditions. A range of prominent structures was fabricated, including, first of all, the unique all-welded bridge across the Dnieper River, named after E.O. Paton. Principles, approaches and structural-technological solutions optimised in designing and construction of this bridge cleared the way to a wide application of welding in bridge construction. That bridge obtained the recognition of the American Welding Society as an outstanding welded structure of the 20th century. The experience gained in construction of the E.O. Paton Bridge was utilised for building other bridges across the Dnieper River in Kiev (Yuzhny, Moskovsky, Gavansky (Habour), Podolsky-Voznesensky, highway and railway bridges), as well as bridges in Dnepropetrovsk and Zaporozhie, and bridge across the Smotrich River in Kamenets-Podolsk.

Development of the technology for deployment of coiled tanks intended for storing oil and oil products was a striking example of the new approach to erection of prefabricated welded structures. This technology provided solution to the problem of reconstruction of the storage tank fleet of the country, which had been destroyed during the Second World War.

Building projects and technologies were developed in collaboration with the Research and Design Institute «Ukrproektstalkonstruktsiya». They were successfully realised in construction of TV towers in Kiev, St.-Petersburg, Erevan, Tbilisi, Vitebsk and Kharkov.

The «Motherland» monument in Kiev is also among the outstanding welded structures.

The Electric Welding Institute gives special consideration to the problem of evaluation of strength of structures containing service defects, estimation and extension of their remaining life. Boris Paton was the initiator and scientific supervisor of the target science-and-technology program «Problems of Life and Safe Operation of Structures, Constructions and Machines». Many research institutes, colleges, branch institutions and a large number of industrial enterprises were involved in accomplishment of this program. Important scientific-and-technical and practical results were generated in working out of methodological principles, technologies, methods and means for estimation and extension of service life of structures. Much consideration is given to development of methods for non-destructive testing and diagnostics. Available are the automated units for ultrasonic inspection of welded joints in large-diameter pipes, bodies of drill bits, power plant components, and welded joints on light alloys and non-metallic materials. Investigations for application of low-frequency ultrasonic waves and contactless introduction of acoustic waves into test objects are underway.

Systems for continuous monitoring of welded structures, which have to meet increased safety requirements, were developed for the first time in Ukraine.

Procedures for prediction of mechanical properties and remaining safe life of welded joints and connections comprising crack-like defects, as well as degradation of materials during operations are available.

For many years the Institute has been active in research in the field of materials science. New structural materials and technologies for their manufacture are being developed, and relationships between composition, structure and properties for different-application materials are being studied. The Electric Welding Institute has become a major materials science centre, with highly qualified specialists conducting the most sophisticated research on materials science in the field of physics of metals, metal engineering, electron microscopy, mass spectroscopy, Auger spectrometry, analysis of gases in metals and welds, X-ray elemental analysis, etc.

In 1954, Boris Paton headed investigations on using the electroslag process for improving the quality of metals and alloys. As a result, a fundamentally new area was formed in metallurgy — electroslag remelting, which gained wide acceptance and international recognition within the shortest terms. It is used to improve properties of heat-resistant, stainless, tool, ball bearing and other steels and special alloys. Many countries throughout the world bought licenses for this process. Production of hollow ingots, pressure vessels, stop valves for heat and nuclear power plants, cast punching tools, marine engine shafts and other critical parts was arranged by combining the process of electroslag remelting and casting.

The work on refining of metals and alloys by the electron beam was started as early as 1959. Electron beam melting turned out to be an efficient method to improve the quality of special steels and alloys based on nickel and iron, and an effective technological process for producing super pure niobium, titanium and many alloys on their base.

Electron beam technology for producing titanium ingots has made good progress over the last years. New high-strength titanium alloys doped with aluminium, zirconium, niobium and iron were developed, and commercial electron beam cold hearth melting units were built. Many of them have no analogues in the world practice.

The process, equipment and technology for plasma-arc remelting of metals and alloys were developed. Capabilities of the plasma-arc technology were enhanced owing to the development of AC plasmatrons, allowing an essential improvement of reliability of the design of melting units and power sources.

Ladle treatment of metallurgical melts has been extensively applied in the world metallurgical practice in the last years. The E.O. Paton Electric Welding Institute developed new types of flux-cored wires, containing highly reactive elements for microalloying, modification and desulphuration of steels and cast iron, as well as technologies and equipment for manufacturing large-diameter flux-cored wires.

The injection metallurgy method is widely applied now at metallurgical works of Ukraine and Russia. Dozens of millions of tons of steel melts have been treated by this method.

The Electric Welding Institute is successfully conducting research in the field of soldering and brazing of metals and alloys. New brazing filler metals and technologies are widely employed for fabrication of components of aircraft engines, space engineering and drilling industry equipment.

Gigantic oil and gas deposits were discovered in the USSR during the post-war years. They are located mainly in Central Asia, Western Siberia, North Urals and other remote regions. So, it was necessary to construct high-capacity main gas and oil transportation systems to transport oil and gas to western regions of the USSR and abroad. Under the guidance of B.E. Paton, the Electric Welding Institute completed a package of work on development of unique ingenious technologies and equipment for flash butt position welding of pipes, namely «Sever» systems. More than 70,000 kilometres of pipelines, including about 6,000 kilometres of large-diameter gas pipelines in the Extreme North, were welded by the flash butt process. The ingenious technology for automatic position butt welding of pipes by using self-shielding flux-cored wire with forced weld formation — «Styk» system — was also developed. This technology was used to construct more than 10,000 km of main gas and oil pipelines, including «Druzhba», «Central Asia–Centre», «Urengoj–Pomary–Uzhgorod», «Khiva–Beineu», «Shebelinka–Izmail», «Yamal–Western Border», «Yamal–Povolzhje», etc., as well as other oil and product pipelines.

Prof. Nikolai K. Baibakov — a major authority in the oil and gas complex of the country, who was the People's Commissar of oil industry during the war years, and then Chairman of the USSR State Planning Committee for more than 22 years, said: «Boris Evgenyevich Paton, the President of the Academy of Sciences of Ukraine and Director of the E.O. Paton Electric Welding Institute, had a tremendous influence on progress of oil and gas construction, and development of oil and gas industry of the former Soviet Union... National manufacturing of arc welded pipes was established with his direct participation... His priority influence on forming the entire welding policy in the oil and gas complex is indisputable. B.E. Paton is making a great contribution to determination of the extremely important parameter of pipelines — their remaining life... The most important point is that all these technologies, machines and welding consumables were brought up to a level of the widest acceptance... Not less is done also on the advanced technologies, and solving the scientific and engineering problems for a new generation of pipeline systems, which will be built in the 21st century».

Boris Paton pays great attention to implementation of the achievements of modern science and technology in medical practice. In the 1900s, he suggested using the welding processes for joining live tissues and organised a creative team of welding scientists and surgeons. This cooperation enabled the development of a new method for joining (welding) soft live tissues. Properties of tissues of different organs of a human body were studied, new welding equipment and methods for control of the welding process were developed, mathematical simulation of the processes of heating of tissues at high-frequency currents flowing through them was performed, and electrophysical properties of the biological tissues and strength of the welded joints were experimentally determined. Electric current sources for the welding units equipped with automatic control systems, and instruments for welding different types of biological tissues were developed. New samples of the equipment were successfully tested by medical establishments. The extensive experience has been accumulated by now — more than 30,000 surgical operations have been conducted on humans. The method of welding live tissues is used in clinics of Kiev and 12 regions of Ukraine, and is being verified in clinics of Moscow, St.-Petersburg, and foreign countries outside the CIS. A shortening of surgical operation time has been achieved, the probability of post-operative complications has been reduced, and blood losses have been decreased. The package of work on welding of live tissues performed under the leadership and with the active creative participation of B.E. Paton was awarded the State Prize of Ukraine in the field of science and technology.

B.E. Paton pays much attention to the international activity of the Institute and its scientists. Collaborative scientific projects, exchanges of delegations and specialists, presentation of research results in prestigious foreign publications, holding of international conferences, training of highly qualified personnel, selling of licenses for materials, equipment and technologies, organising of international exhibitions and participation of the Institute scientists in them — this is a by far incomplete list of international activities of the Institute. «Avtomaticheskaya Svarka» (The Paton Welding Journal), «Special Electrometallurgy» and «Technical Diagnostics and Non-destructive Testing» journals are published and translated into English under the guidance of Boris Paton. This enables informing the international scientific-and-technical community of the results of research and new developments of the Institute.

Dozens and hundreds of talented scientists and engineers have grown at the Institute. There is a considerable number of academicians and corresponding members of the NAS of Ukraine among the patonovites. Associates of the Institute defended over 130 doctoral and more than 700 Ph.D. theses. Many developments mentioned above are the result of the work of a large and united team. The unity of the team is provided by personal traits of its leader — Boris E. Paton.

One of the basic principles set forth by E.O. Paton when founding the Institute, and further developed by B.E. Paton, is conducting a purpose-oriented fundamental research and keeping a close connection between science and manufacturing. This principle has been consistently implemented during an almost 75 years' history of the Institute. Scientific departments of the Institute, design department, experimental shops, experimental design-technological bureau, engineering centres, experimental productions and pilot plants have been established during the entire history of the Institute. These are integral links in the system of organisation of research and introduction of its results into production. Realisation of this system allowed the development of unique structures, equipment, materials and technologies, the application of which had a great influence on progress of many industries, namely mechanical engineering, shipbuilding, rocket-space complex, aircraft engineering, power generation, mining industry, metallurgy and chemical production, development of pipeline transportation systems, construction industry, etc.

Dedicated activity of the Institute staff was highly appreciated by the state. The Institute was awarded the Orders of Lenin, October Revolution, Labour Red Banner, and many of the Institute employees were awarded the orders and medals of the USSR and Ukraine. Nine developments, in which associates of the E.O. Paton Electric Welding Institute were involved, received the USSR Lenin Prizes in the field of science and technology, 24 developments were awarded the USSR State Prizes, and 34 developments — the State Prizes of the Ukrainian SSR and Ukraine. Many years of selfless efforts of the Institute staff led by Boris E. Paton have won it the worldwide recognition.

In 1962, Boris Paton was elected a Full Member (academician) of the USSR Academy of Sciences in speciality «Metallurgy and Technology of Metals». In that same year the scientists of the Academy of Sciences of the Ukrainian SSR unanimously elected B.E. Paton the President of the Academy. Since then, for 46 years he has been heading this leading scientific organisation of Ukraine. According to the charter of the Academy, the presidential elections are held every five years, and Boris Paton was re-elected to this post nine times. Profound understanding of the role of science in society, its goals and objectives, high international scientific authority, devotion to science, inexhaustible energy and high moral standards, social and political activity, and experience of leading a large scientific staff became the decisive arguments for election of Boris Evgenyevich to the post of the President of the Academy of Sciences of Ukraine. In this key position his talent of the organiser of research became even more evident. A new structure of the Academy of Sciences and its new Charter were developed under his leadership. They are aimed at the most efficient use of the scientific potential and means, their focusing on solution of the most important fundamental problems of science, having a crucial importance for economy of the country.

Dozens of new institutions and organisations were set up in the system of the Academy of Sciences of the Ukrainian SSR by the initiative of B.E. Paton and with his active support, thus allowing performance of more extensive and profound studies in the most important scientific areas. He is constantly insisting on precise definition of the scientific profile of each institute, making sure that each of them becomes the leading organisation in its field in the Republic, state and in the world. He takes drastic measures to ensure that all the academic institutes are provided with up-to-date materials and technical facilities. He organises extensive housing construction for the Academy staff, and a whole new region of Kiev, called Akademgorodok, was thus founded.

The Academy of Sciences of the country became the chief scientific centre of the country, where extensive research is performed on urgent problems of natural, engineering, social sciences and humanities. Institutions of the Academy take up significant positions in individual sectors of mathematics, theoretical physics, solid-state and low-temperature physics, radiophysics and radioastronomy, materials science, cybernetics and computer engineering, neurophysiology, molecular biology, microbiology, virology and genetic engineering, and in a number of other fields of knowledge. Unique and high-capacity pilot-production base was formed within the Academy, and new types of relations between science and manufacturing gained acceptance.

Academic research centres were set up by the initiative of B.E. Paton in different years in a number of the country regions — Donetsk, Lvov, Odessa, Kharkov, Dnepropetrovsk and Simferopol. The research centres have the functions of regional inter-industry bodies for coordination of scientific activity.

In 1963, B.E. Paton was elected a Member of the Presidium of the Academy of Sciences of the USSR. His work in this position allowed him to become familiarised with the activities of institutes of the Academy of Sciences of the USSR, study the experience of functioning of the Presidium and its departments. Trustful business relations and creative contacts were formed between B.E. Paton and academician M.V. Keldysh, President of the Academy of Sciences of the USSR, which were then developed into friendship and mutual respect.

Boris Paton formed good businesslike relations with V.A. Kirillin, Chairman of the USSR State Committee on Science and Technology, A.P. Aleksandrov, G.I. Marchuk and Yu.S. Osipov, Presidents of the Academy of Sciences of the USSR, M.A. Lavrentiev, founder and first Chairman of the Siberian Division of the Academy of Sciences of the USSR, and many other scientists. This allowed organising cooperation of Ukrainian scientists with scientists from Moscow, Leningrad, Novosibirsk and other regions of the Russian Federation and other Soviet republics, and, without doubt, promoted progress of science in Ukraine.

Close cooperation between the Academy of Sciences of the Ukrainian SSR, Academy of Sciences of the USSR, USSR State Committee on Science and Technology and academies of sciences of the Union republics promoted progress in many new scientific areas in Ukraine, establishment of new institutes and engineering centres, and consolidation of international reputation of the Academy of Sciences of Ukraine.

Boris Paton initiated major integrated science-and-technology programs for individual industries, transportation, communications and agriculture. Scientists of the Academy made an outstanding contribution directly to solving the urgent problems of development of the national economy. This form of organisation of the scientific activity was universally recognised.

Boris Evgenievich was the organiser of a number of scientific councils. In 1966, he was at the head of the USSR Scientific Council on problem «New Welding Processes and Welded Structures». The Council united the USSR scientists and specialists, and was functioning effectively from 1958 till 1991.

In 1972, the International Scientific-and-Technical Council of the COMECON Member-Countries on welding problems was set up by the initiative of Boris Evgenyevich. Owing to the activity of the Council, which was successfully functioning till 1992, many scientific and engineering organisations of the COMECON Member-Countries grew to the state-of-the-art research level, and had a great influence on progress of welding in their countries.

Following the advice of M.V. Keldysh, B.E. Paton organised the Scientific Council at the Presidium of the Academy of Sciences of the USSR on problem

«New Processes of Manufacturing and Treatment of Metallic Materials», which united scientists of academic institutions and specialists of many other departments, and promoted development of materials science in the Academy of Sciences of the USSR, Russian Academy of Sciences and National Academy of Sciences of Ukraine. Many materials scientists and metallurgists, who were active at the Council, were elected into the Academy of Sciences of the USSR and Russian Academy of Sciences with the support of Boris Evgenyevich, and made a great contribution to development of the materials studies.

Boris Paton has the fundamental understanding of the role and place of science in addressing humanitarian problems of the society. While placing high emphasis on development and commercial application of advanced technologies, he, at the same time, seeks substantiated scientific estimates of their effect on the environment and humans. Led by Boris Paton, big teams of scientists of the Academy made predictive estimates of the negative ecological and social-economic consequences of large-scale drainage and irrigation meliorations in Ukraine, intensive chemisation of agriculture, and diversion of part of the runoff of the Danube and Dnieper Rivers.

Boris Paton adhered to his principles also in the issue of construction of a nuclear power plant in the Chernobyl region. Unfortunately, his warnings were fully confirmed by the universally known events of 1986 at the ChNPP. Outstanding capabilities of Boris Evgenyevich Paton as a leader, scientist and organiser were fully revealed during the memorable days of the Chernobyl tragedy. Teams of many institutes of the Academy of Sciences of the Ukrainian SSR and its Presidium became involved in the activities on liquidation of consequences of the accident from its very first days. Hundreds of scientists, specialists of the Academy of Sciences, ministries, departments, and enterprises of Ukraine took part in this work. Boris Paton led the efforts on preparation of proposals for decision-making authorities of Ukraine and the USSR Government Commission. Later on, in September 1997, B.E. Paton headed the Advisory Board of Independent Experts on finding comprehensive solutions to the problems of the Chernobyl Nuclear Power Plant, newly established by the President of Ukraine.

In 2004–2005, the «Academperiodika» Publishing House published the two-volume edition «Chenobyl 1986–1987». Documents given in this fundamental work provide an objective and comprehensive coverage of the role of the Academy of Sciences of the Ukrainian SSR and self-sacrificing efforts of the staff of the academic institutes under the leadership of its President. The goals defined by the President are being successfully pursued even now by the staff of many academic institutes. The team of the Institute for Problems of Safety of Nuclear Power Plants and expeditions from many other institutes of the NAS of Ukraine are continuously working in Chernobyl.

After disintegration of the Soviet Union and formation of independent Ukraine, under conditions of long-term economic and financial crisis, which did not spare the Academy, its President managed to preserve the Academy and its major scientific schools.

The status of the Academy as a supreme government research organisation was secured at the legislative level, principles of its academic self-administration were preserved, its restructuring was accomplished in keeping with the new conditions, and fundamental and applied studies were focused on addressing the urgent problems of formation of the state. New priorities were identified in the field of natural, engineering, social sciences and humanities. A number of new institutes and centres of socio-humanitarian profile were established.

The world level of research was preserved in several areas of mathematics, informatics, mechanics, physics and astronomy, materials science, chemistry, molecular and cell biology, and physiology. The contribution of scientists of the Academy to fundamental and applied research in Ukraine is increasing. New technologies, materials and computer facilities have been developed, and new mineral deposits have been discovered, etc.

The Institute of Economics, Institute for Economic Forecasting, Institute for Economic and Legal Research, Institute for Market Problems and Economic-and-Ecological Research, Institute of Regional Research, Institute for Demography and Social Studies, Institutes of Ukrainian Studies, Oriental Studies, Political and Ethnic Studies, Sociology, Ukrainian Archaeography and Source Studies, Ukrainian Language, as well as other departments, institutions and centres have been established and are successfully functioning.

The Institutes of the Academy take an active part in working out of the innovative programs on economic development of Ukraine, investigation of its history, culture and language.

Organisation of fundamental and applied research is being improved, and priorities are being determined in development of individual scientific areas and interdisciplinary studies. Among them are such programs as «Nanosystems, Nanomaterials and Technologies», «Sensing Systems», «Intelligent Information Technologies», «Hydrogen Power Generation», «Power Saving», «Problems of Demography and Development of Mankind», etc.

Boris Evgenievich is continuously concerned about young scientists, attracting talented young people into science, supporting them financially and trying to improve their living standards. Youth scientific projects are being funded, and dormitories for post-graduates are being built and reconstructed.

B.E. Paton makes a lot of efforts for preservation and development of international scientific cooperation and foreign economic contacts with business partners from foreign countries. Ukrainian scientists participate in many collaborative programs. Project competitions have been conducted together with the Science and Technology Centre in Ukraine, Russian Foundation for Fundamental Research, Russian Humanitarian Sciences Foundation and Siberian Division of the Russian Academy of Sciences.

B.E. Paton is one of the initiators of formation and preservation of common scientific space within the Commonwealth of the Independent States. In 1993, the International Association of the Academies of Sciences (IAAS) was established, which united national academies of 15 countries of Europe and Asia. Boris Evgenyevich is the permanent President of this Association. The Scientific Council of IAAS on Advanced Materials is functioning under his direction.

Academician B.E. Paton is an Honorary President of the International Engineering Academy, member of the Academia Europaea, Honorary Member of the Roman Club, International Academy of Technological Sciences, Honorary Member of the International Academy of Sciences, Education and Arts, International Aeronautical Academy, Foreign Member of the academies, universities and scientific-and-technical societies of many countries.

B.E. Paton performed and continues performing extensive public work. He was many times elected a Deputy of the Supreme Soviet of the USSR and Ukrainian SSR, Deputy Chairman of the Council of the Union of the USSR Supreme Soviet, member of the Presidium of the Supreme Soviet of the Ukrainian SSR, member of the Central Committees of the Communist Party of the Soviet Union and Communist Party of Ukraine. He was a head and member of different high committees and commission. The list of his positions is very impressive. He is successfully working in these positions owing to the deep sense of personal responsibility to the state, people and his own conscience.

In addition, he has such traits as outstanding organisation, efficiency, rare ability of precisely grasping the point, and immediately making the right decision.

This heavy load is made easier to bear by his good physical shape, which he has preserved up to now owing to his active life style, regular and dedicated sports activities, including tennis, water skiing and swimming.

Yu.S. Osipov, President of the Russian Academy of Sciences, has been the B.E. Paton's friend and cooperation partner for many years. Characterising Boris Evgenyevich, he said: «The life of B.E. Paton — in science, in the sphere of research organisation and practical implementation of scientific achievements, his public and state activity — is truly a great feat for the sake of the scientific progress and for the sake of the future».

For his great services to the science and the state, B.E. Paton was awarded the high titles of the Twice Hero of Socialist Labour of the USSR and Hero of Ukraine. He is the knight of four Orders of Lenin, Orders of October Revolution, Labour Red Banner, Friendship of Nations, orders of Prince Yaroslav the Wise of the 4th and 5th Degrees (Ukraine), Order «For the Services to Motherland» of the 2nd Degree (Russia), Order of Frantsisk Skorina (Republic of Belarus), Order of Honour (Georgia), Order «Dostyk» (Republic of Kazakhstan), and many other awards of the CIS countries. B.E.Paton is a laureate of the Lenin and State Prizes of the USSR and Ukraine in the field of science and technology. He was awarded the M.V. Lomonosov, S.I.Vavilov and S.P. Korolyov Gold Medals, A.Einstein Silver Medal of UNESCO, and many other prizes and decorations.

Boris Evgenyevich is utterly devoted to the science, Institute, Academy and Motherland.

Today it is impossible to imagine the Electric Welding Institute and National Academy of Sciences of Ukraine without B.E. Paton. His worldly wisdom, tremendous experience and international authority in science and society allowed preserving the scientific potential of Ukraine.

Boris Paton is a leader, fighter, creative personality, deeply decent and kind man, possessing fantastic energy and capacity for work, enormous experience, deep knowledge in many areas, and ability to continually learn. He has a generous nature and quick analytical mind. He is democratic, well-wishing, open for communication, affable, and always ready to support a person in need and help him.

It is symbolic that Boris Evgenyevich was born on the day of foundation of the National Academy of Sciences of Ukraine. In 1998, at the celebration of the 80th anniversary of the Academy and its President, the huge hall of the «Ukraine» palace rose in applause after the announcement that B.E. Paton was the first person in the country to be awarded the title of the Hero of Ukraine.

This is the kind of person our dear Boris Evgenyevich is.

Boris Paton is meeting his 90th birthday full of creative ideas, indomitable wish to work and enhance the contribution of science to prosperity of our state — the independent Ukraine. Let us wish him new successes, good health and much happiness with all our hearts.

Prof. I.K. Pokhodnya
Academician
National Academy of Sciences of Ukraine

WELDING AND RELATED TECHNOLOGIES FOR MEDICAL APPLICATIONS

B.E. PATON
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Considered are R&D efforts and experience of using welding and related technologies in different medical applications: electric welding of soft live tissues to join damaged tissues and recover vital activity of human and animal organs; hyperthermic methods for welding, cutting and treatment of live biological tissues; magnetron sputtering of coatings used to cure cardiovascular diseases; implants, prostheses and surgical instruments of shape memory alloys; bioceramic microplasma coatings for endoprostheses; composite materials produced by using nanotechnologies for targeted transportation of medical preparations in a living organism; and steam-plasma technologies for disposal of medical wastes.

Keywords: *electric welding of soft live tissues, hyperthermic welding methods, magnetron sputtering of coatings on stents, implants, prostheses of shape memory alloy, bioceramic coatings on endoprostheses, magnetic nanoparticles for transportation of medical preparations in living organism, steam-plasma technologies for disposal of medical wastes*

Wide application of welding as an enabling technological process in many fields of current activity is greatly related to the general level of science and technology. In-depth theoretical and experimental studies of welding and allied processes allow fabrication of new structures, including unique ones. At present we can confidently state a good progress in a number of research and development fields on using welding and related technologies in different areas of medicine.

Referring to history, the first evidences of using high-frequency electric coagulation equipment in medicine were fixed about 100 years ago. However, it was a very long way before it became possible to produce reliable joints in damaged tissues and recover vital activity of human and animal organs by the electrosurgery methods.

Having taken this way, the E.O. Paton Electric Welding Institute in collaboration with a number of medical organisations of Ukraine started developing electric welding for joining soft live tissues. Positive results of the work on development of different welding methods, special electric welding equipment, power sources and ingenious systems for automation of the welding processes tested in joining cuts of the live tissues were presented to medical specialists of Ukraine, Russia, Belarus and USA, and generated their interest.

At the same time, the E.O. Paton Electric Welding Institute is active in other areas of using welding and related technologies in medicine. They include: methods for plasma and thermal-jet welding, cutting and treatment of live biological tissues; making of surgical instruments, implants and prostheses of shape memory alloys; development of composite materials by using nanotechnologies; and application of steam-plasma processes for disposal of medical wastes. Consider these areas in more detail.

Electric welding of soft live tissues. The high-frequency equipment applied in surgery has been used up to now only for dissecting soft tissues and arresting bleeding. In this case, the organs being operated automatically lose their functions, which do not recover later on. We set our minds on realising the dream of surgeons about the possibility of rapidly and bloodlessly cutting an organ to be operated with a minimal damage of its tissues, and quickly joining the tissue incision using no sutural material, as well as the possibility of recovering physiological properties of the live tissues and maintaining functions of the operated organs.

The first experiments in this area were conducted in 1993. They proved the feasibility of joining incisions of live tissues under certain conditions. A team of specialists that started accomplishing project «Electric Welding of Soft Live Tissues» was formed in 1996 to achieve this challenge, which was pioneering for the world practice. The team included scientists and engineers of the E.O. Paton Electric Welding Institute, engineers of International Association «Welding», professors and doctors of a number of different-profile institutes and clinics of Kiev (A.A. Shalimov National Institute of Surgery and Transplantology of the Academy of Medical Sciences of Ukraine, «Okhmatdet» clinic, Central Clinical Hospital of the Security Council of Ukraine, etc.). American Financial Company «Consortium Service Management Group, Inc.» was involved in addressing this challenge. Initial investigations into welding of live tissues were carried out on more than 1000 experimental animals (white rats, rabbits and pigs).

High-frequency power source samples with a microprocessor control system and bipolar welding instruments were developed to conduct the experiments.

The challenge to be addressed was extremely difficult, because the live tissue is non-homogeneous, having different structure and properties in different organs. For example, the intestine or vessel wall consists of several layers of tissue performing different functions and having different physical properties. The age of tissue also affects its properties. Investigations were conducted to study conditions of formation of a welded joint using the high-frequency current

Figure 1. Certificates of state registration in Ukraine and Russia

modulated in a special way. For welding live tissues the electric thermomechanical impact was selected so that the full-value live tissue could substitute for the weld with time. As proved by the systematic studies, the main condition for producing a joint in welding of live tissues is violation of integrity of cell membranes, denaturation and coagulation of protein. At present, it can be concluded that the welding process is accompanied by only a partial coagulation of protein, elastin and collagen, which form a structural union of molecules or joining of the live tissue under mechanical compression with the bipolar electrosurgical instrument. The data of histological and histochemical studies show that structural components of the denaturated protein retain in general their characteristic state under the dosed and controlled energy effect, and it is this fact that is responsible for the phenomenon of partial preservation of the live connective tissue. Strength of the joint, e.g. on intestines, is provided by a flow of the high-frequency electric current and mechanical compression of muscle fibres of the intestine wall in coagulation of protein structures. The welding process results in formation of a joint without any scar, as after some time the organ tissue recovers almost completely its morphological structure. For instance, it was found out that after a certain time the blood vessels of the thick intestine wall grow through the intestine joining line. It is proved that strength of such a joint is not lower than natural strength of the thick intestine. The tissue welded is not burnt during the operation. Recovery of the physiological function of the destroyed organ occurs quickly, and is not accompanied by development of any complications. Such results can be obtained only by complying with very high requirements to the control system for welding of live tissues. At the same time, it is important that control be simple for a surgeon and do not distract him from performing his main task.

In 1998, the experiments were conducted on welding using extracted human organs, and then organs to be extracted by medical indications. The positive results were obtained from applying the welding technology, and its reproducibility was proved by carrying out a large series of surgical operations on animals and extracted human organs. This gave grounds to the Ministry of Health of Ukraine to grant the Certificate of State Registration to the welding equipment developed by the E.O. Paton Electric Welding Institute and manufactured by International Association «Welding», and permit its application in medical practice in 2001–2004 and 2005–2010 (Figure 1). The registration certificate and permission of application of the said equipment and technology in medical practice were also received from the Federal Health Control Agency of the Russian Federation. Based on comprehensive tests of the welding equipment, the Ministry of Health of Belarus also decided on the possibility of applying this equipment in medical practice. The equipment for welding live tissues is covered by appropriate certificates.

The equipment for welding live tissues consists of power source EK-300M1 with a control system (for application in clinics for human surgery) and power source EK-150 (for veterinary medicine) (Figure 2). A set of the required medical welding instruments, such as forceps, clamps and laparoscopic forceps, as well as assembly-welding devices for making circumferential joints on hollow organs (Figure 3), was developed to perform different surgical operations. This equipment with a set of instruments has four main functions:

- welding in the automatic mode;
- welding of blood vessels;
- welding of massive tissues (single-stage welding of intestines, removal of part of a lung with simultaneous welding up of edges, removal of big tumours with single-stage arrest of bleeding);
- cutting of tissue with simultaneous closing of small vessels (removal of part of an organ, e.g. liver, kidney or spleen, by maintaining their vital activity).

The level achieved in the above efforts allowed the medical welding technology to be used currently to advantage in such areas as general surgery, traumatology, thoracic surgery, gynaecology, proctology, urology, mammalogy, general abdominal surgical operations, otolaryngology, and vascular surgery. Over 70 surgical procedures have been mastered. Some examples of methodical approaches to conducting surgical operations by using the welding technology without any sutural material are shown in Figure 4.

Utilisation of the welding technology provides a substantial, in some cases a few times, reduction of duration of a surgical operation, and shortening of the

Figure 2. Power sources EK-300M1 (*a*) and EK-150 (*b*) for welding live tissues

time of anaesthesia applied to a patient. The operations are performed in the so-called «dry operative field», the blood losses being decreased from 3 to 6 times. The need to use medicines, including narcotic analgesics, in the post-operative period is decreased. The process of recovery of the morphological structure of a destroyed organ is accelerated from 2 to 5 times. No case of suppurative inflammation of the tissues subjected to welding has been fixed. This is related to the absence of foreign bodies and necrotic tissue in an organism after the operation. Application of the welding technology provides increased cost effectiveness of the operations, as no sutural materials and no clips are used, and there is no need to employ extra surgical instruments. Often the use is made of only one welding instrument and one welding device.

The welding technology can be used both in planned operations because of chronic diseases, and in emergency surgery, e.g. because of injuries of sound organs.

Clinical application of the method for electric welding of soft live tissues is progressively increasing and finding more and more supporters among surgeons. The range of operations carried out by using this method is constantly widening. In addition to making the work easier for surgeons, this new technology is capable of alleviating sufferings of many millions of people who have to be subjected to surgical operations.

Not long ago, the famous surgeons, having heard that welding intrudes into the holy of holies — a human organism, showed perplexity, expressed irony and charged welders with being superficial. Today the welding technology is successfully applied in new and new fields of surgery. This method is covered by the patents of Ukraine, Russia, USA, Canada, Europe and Australia [1—17].

Application of the welding method in different fields of general and specialised surgery was mastered in 35 clinics of 12 regions of Ukraine and 2 leading clinics of Moscow and St.-Petersburg. About 30 thousands of surgical operations using the welding technology have been performed on different human organs up to now.

Hyperthermic methods for welding, cutting and treatment of live biological tissues. In 2001, the Design Bureau «Yuzhnoe» and E.O. Paton Electric Welding Institute jointly developed the surgical plasma system «Plasmamed». This event launched research and development in a new medical area — hyperthermic surgery.

The first stage of the R&D efforts included building of equipment capable of cutting parenchymatous tissues and arresting intra-wound bleeding by using the low-temperature plasma jet. The equipment had positive medical-technical assessment, and the procedure for plasma welding of live intestine and stomach tissues, as well as method for joining edges of wounds of the parenchymatous organs were developed.

As a follow-up to these efforts, the E.O. Paton Electric Welding Institute in collaboration with the A.A. Shalimov National Institute of Surgery and Transplantology developed the thermal-jet method and equipment for welding live biological tissues. This method is characterised by simplicity, availability of the equipment developed for it, and utilisation of ambient air instead of argon. Several modifications of laboratory models of the thermal-jet surgical instru-

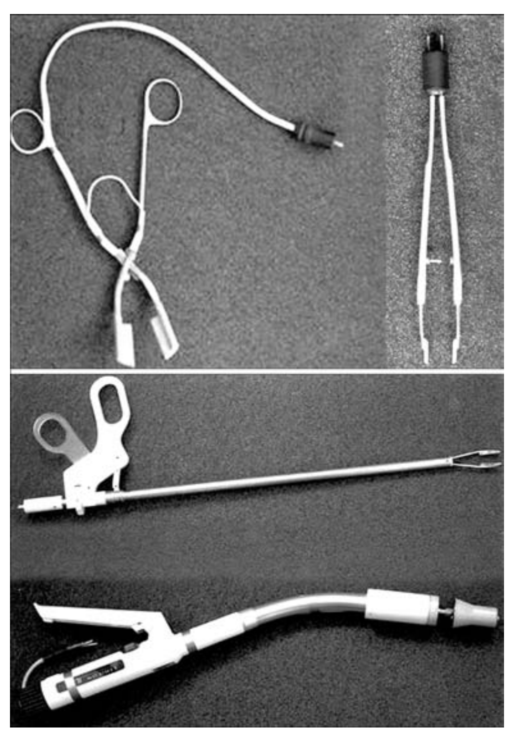

Figure 3. Set of medical welding instruments for different types of surgical operations

Figure 4. Types of welded joints on live tissues: *a* — hermetic joint on intestines (intestinal anastomosis); *b* — closing of large vessel; *c* — single-stage hermetic resection of part of a lung

ments and power sources for them were developed. The power they consume is no more than 20 to 60 W. Total weight, together with a power source, is not in excess of 1 kg, this making them suitable both for stationary and field conditions, including with the power supplied from the AC mains or accumulator.

This method was modified for treatment of purulent surgical wounds (Figure 5), prevention of wound infections in gunshot injuries of tissues, as well as for arresting of intra-wound bleeding. Microbiological and histological studies of samples of the laboratory animal tissues showed the high efficiency of this method used for sanitary treatment of wounds infected with strains of microorganisms resistant to antibiotics (such as staphylococcus aureus, etc.). No pathogenic microflora has been detected in wounds after the thermal-jet treatment. At present, this method and models of the equipment are subjected to pre-clinical tests.

Figure 5. Thermal-jet treatment of chronic purulent wound

Along with the above applications of the thermal-jet method for welding and treatment of live tissues, the efforts have been started to develop the hyperthermic method for killing malignant tumours of solitary metastases, this being a pressing and promising area of research. Novelty of the developments has been proved by the patents of Ukraine [18–20].

Magnetron sputtering of coatings on stents. The range of the new approaches to treatment of cardiovascular diseases, which gained acceptance during the last 20 years, includes invasive methods consisting in introduction of foreign bodies in the form of metal structures (stents) into the vessel lumen to maintain its required cross section. Almost 2 million operations on stenting were performed in the world in 2000. Predicted annual growth of the number of such operations is 20–25 %. The use of this treatment method is facing the problem of the probability of recurrence of a disease, i.e. restenosis. This is related to growth of the fibrous-connective tissue in the form of a capsule around a stent, which is a reaction of an organism to introduction of the stent. One of the solutions to this problem is development of special coatings for the stents.

The E.O. Paton Electric Welding Institute, in collaboration with the P.L. Shupik National Academy of Post-Diploma Education of the Ministry of Health of Ukraine and the G.V. Kurdyumov Institute for Metal Physics of the National Academy of Sciences of Ukraine, is active in finding compositions of coatings that are «invisible» for the internal environment of a human organism. Zirconium and its alloys were selected as materials for such coatings. The coatings were deposited by the method of magnetron sputtering on steel 10Kh18N10T (0.18–0.50 mm thick plates, and 0.3–0.5 mm diameter wire), which is widely applied in medicine, including for the manufacture of stents. The coatings were 3–5 μm thick.

The efficiency of using the magnetron sputtered zirconium coatings for diminishing reaction of an organism to installation of a stent was assessed by the results of experiments on live samples. The experiments were conducted on rabbits by hypodermically installing the 10Kh18N10T steel plates with and without the coating. The plates were extracted from an organism after 8 weeks and subjected to histological studies. Results of the studies showed that thickness of the fibrous-connective capsule around the 10Kh18N10T steel plate was 232.4±10.7 μm, whereas in a case of the zirconium coated plate it was 56.3±±11.9 μm. Surface of the 10Kh18N10T steel plate was substantially damaged by corrosion, whereas no signs of corrosion were detected on the surface of the zirconium coating.

The data obtained allow a conclusion that application of the magnetron sputtered zirconium coatings provides a four times decrease in reaction of an organism to stainless steel 10Kh18N10T, and is efficient for the use of stents made from this steel in terms of decreasing the risk of restenosis.

Implants, prostheses and surgical instruments of shape memory alloys. It is a known fact that shape memory alloys deformed at low temperatures restore their shape in heating as a result of phase transformations. Out of a wide variety of shape memory alloys, only the titanium- and nickel-base alloys, i.e. so-called nitinols and titanium nickelides, are suitable for medical applications, as they have high anticorrosive properties, close to those of pure titanium, and necessary bioinertness and biocompatibility characteristics.

It is very important for practical application in medicine that restoration of shape should occur at a temperature of the human body, i.e. from 30 to 35 °C. At the same time, it is desirable that before the surgical application a piece, which in heating should acquire the shape of a spiral, be deformed, e.g. stretched into a line, in cooling to a running water temperature, i.e. approximately 10 °C. New titanium- and nickel-base shape memory alloys jointly developed by the G.V. Kurdyumov Institute for Metal Physics and E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine correspond to the above conditions, as the temperature range of phase transformations in these alloys meets the safe medical application requirements.

The E.O. Paton Electric Welding Institute designed and manufactured implants and instruments of these alloys. Some of the developed implants and instruments to manipulate them, such as extractors, clips, pessaries, emboli and stents, passed clinical tests.

Extractors are intended for removal of stones from tubular human organs. The use of nitinol with additional heating to a temperature of about 40 °C allows increasing stiffness of an instrument, thus facilitating separation of walls of a tubular organ and providing unimpeded passage of the instrument through bends, while changing the angle of convergence of branches makes it easier to grip an object or throw it out from the basket. This new design of an extractor was successfully tested in operation on removal of stones from ureter.

Clips (Figure 6) made from a shape memory alloy are applied to join fragments of bones in operations on the locomotor system, as well as in craniocerebral and stomatologic operations. The use of a shape memory alloy makes it possible to substantially simplify installation of the clips, compared with known stainless steel samples. The X-ray photograph shows joining of the elbow joint bones.

The pessary put on the neck of uterus has the form of a spiral, which contracts at a temperature of the human body. The technology was developed for chemical silvering of this spiral with the bactericidal effect, and the applicator simplifying the process of its installation.

Emboli of a new shape (Figure 7), which are made from nitinol, are applied to treat oncological diseases of different organs. They can be easily moved via blood vessels and fixed in a target place corresponding to the kind of a disease.

Nitinol stents of a new design (Figure 8) have an increased stiffness in the radial direction owing to the developed tubular shape, and sufficient axial flexibility to provide their passage via blood vessels to the target installation place. Peculiarity of such a stent is its porous surface, which allows preservation of a large portion of pharmacological properties to prevent restenosis. Testing the new stent filled with corvitin (preparation developed by the A.A. Bohomolets Institute of Physiology of the NAS of Ukraine) on animals proved that it provided the suppressed growth of the connective tissue.

Nitinol stents for gall ducts have been developed and are subjected now to pre-clinical tests. These stents are intended for improving the quality of life after oncological operations. In fact, they are prostheses of the gall ducts in a region where a tumour was removed as a result of the surgical operation. Self-adjustment of the stent in diameter of the duct makes surgical manipulations much simpler. Such stents have no analogues in modern medical practice. The work is underway on development of the instrument to install and hold the stent until the procedure is finished.

Figure 6. Clips for joining elbow joint bones

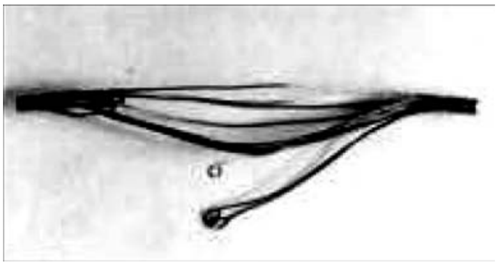

Figure 7. Emboli for treatment of oncologic diseases

The shape memory alloy with ferromagnetic properties was developed. This alloy can find application in the cases where it is necessary to subject the damaged region of a body to heat treatment. Easy transdermic (intravascular) introduction of the instrument of such an alloy to the target place and subsequent induction heating will allow the temperature to be increased within the prescribed ranges. Novelty of the solutions in all of the above efforts is confirmed by the patents of Ukraine [21–27].

Bioceramic microplasma coatings for endoprostheses. The progress of practical surgical treatment of diseases of the joints and injuries of the locomotor system by installing endoprostheses requires an increasingly wide application of metal implants with coatings of bioceramic materials. Mechanical strength of the metal base in such implants combines with biological peculiarities of the bioceramic coating, thus exerting a triple positive effect: increase in the rate of formation of bone tissue, possibility of formation of bond with the bone (osteointegration), and decrease in formation of metal corrosion products.

The E.O. Paton Electric Welding Institute developed the ingenious equipment and technology for microplasma spraying of bioceramic coatings (hydroxyapatite, tricalcium phosphate). Main factors of microplasma spraying affecting the phase composition and structure of the bioceramic coatings were determined, and the extent of impact by each of them was evaluated [28].

Distinctive features of the new technology are the possibilities of controlling the crystalline to amorphous phase ratio in a coating (from 70/30 to 98/2), decreasing the degree of decomposition of hydroxyapatite and the risk of occurrence of toxic phases (CaO), and forming the bioceramic texture in the coating corresponding in its direction to the natural bone tissue. All this increases the degree of biocompatibility, favours the optimal process of fixation of the endoprosthesis in an organism, and its long-term reliability.

Microplasma spraying of two-layer coatings, where first a layer of the titanium coating with bimodal porosity, and then a layer of bioceramics (e.g. hydroxyapatite) are deposited on the titanium substrate of an implant, makes it possible to increase the strength of adhesion of the bioceramic coating to the implant, on the one hand, and provides a more reliable bond of the implant to the bone, on the other hand. Testing this structure of the microplasma coating showed its advantage in strength of adhesion to the bone over a widely spread world practice of sintering spherical titanium particles on the implant surface. The E.O. Paton Electric Welding Institute develops microplasma coatings for endoprostheses in collaboration with the Institute of Orthopaedy and Traumatology of the Academy of Medical Sciences of Ukraine, Institute of Oncology of the Academy of Medical Sciences of Ukraine, and Kharkov Institute of Orthopaedy and Traumatology. The patent of Ukraine on the metal-ceramic implant with the microplasma bioceramic coating for intervertebral spondylosyndesis was received jointly with the Simferopol Medical University [29]. Results of these efforts have been successfully used in practice of deposition of the hydroxyapatite coatings on implants for cement-free knee-joint endoprostheses, as well as on cages for surgical treatment of patients with unstable forms of degenerative-dystrophic diseases of the vertebral column.

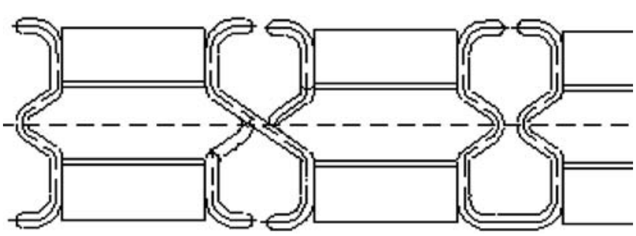

Figure 8. New design of nitinol stents

At present, the E.O. Paton Electric Welding Institute, together with the Institute of Orthopaedy and Traumatology of the Academy of Medical Sciences of Ukraine and Motor Sich, Ltd. is completing development of a new design of the hip joint endoprosthesis with a new type of the microplasma coating. It is planned that a follow-up will be arrangement of production of such endoprostheses.

Medical-application composite materials produced by using nanotechnologies. The processes of electron beam evaporation and subsequent condensation of different materials in vacuum make up a unique technological package, which makes it possible to produce new materials. Materials in the vapour phase «know nothing» about the solubility laws. Therefore, by simultaneously evaporating several materials, mixing their vapour flows and then condensing them on the substrate, it is possible to produce such combinations and proportions of components, and provide such structures, which are very hard or impossible to achieve by other methods.

Up to now the E.O. Paton Electric Welding Institute has accumulated substantial technological experience in «designing» of new inorganic materials and coatings, as well as in production of single- and multiple-phase metallic and ceramic condensates over a wide range of shapes and sizes of structural elements. Sizes of grains, particles, phases and pores, and thickness of microlayers can be varied from several nanometres to 5–10 micrometres. The technology of this level of precision belongs to a category of the advanced nanotechnologies.

Characteristic relationships were determined between structure and properties. Thick condensates can be produced in the form of coatings on parts, in the form of foils, sheets or products separated from the substrate, or in the form of discrete structures (nanopowders).

Thermal barrier graded coatings of the metal–ceramics system take a leading position in the field of practical application. The high level of mechanical properties has been achieved in an area of composite materials with the metal matrix (aluminium, copper, iron, nickel and their alloys) and nanoparticles of refractory oxides uniformly distributed in the matrix. These materials are produced by simultaneous independent evaporation of metal (alloy) and oxide from two sources, followed by condensation of a mixed flow.

As proved by the experiments conducted by the E.O. Paton Electric Welding Institute, this approach can be applied to produce the so-called colloidal systems for medical applications, e.g. magnetic fluids. These systems are easy to produce by using a removable inorganic (or organic) matrix with nanoparticles of the second material, non-interacting with the matrix, which were initially added to it by evaporation and condensation [30].

Figure 9, *a* and *b*, shows magnetic Fe_3O_4 nanoparticles produced from the aqueous solution by a simple technological cycle: combined evaporation of NaCl and Fe_3O_4 from two independent sources, subsequent condensation of the mixed vapour flow on the steel substrate, separation of the condensate from the substrate, and dissolution in water. Mean size of the Fe_3O_4 particles can be gradually regulated from 2 to 15 nm by varying the substrate temperature within 250 °C. Stabilisation of the particles is provided by standard methods, i.e. additions of biocompatible polymers (dextrin and polyvinyl alcohol). The Fe_3O_4 particles can be readily replaced with magnetic nanoparticles of nickel, cobalt or their alloys by substituting nickel or cobalt for the Fe_3O_4 ingot being evaporated. Also, it is possible to design a two-layer (composite) nanoparticle by introducing a corresponding addition, e.g. copper, from the independent third source into the vapour flow.

Intensive investigations are underway now to study the possibility of using magnetic nanoparticles for targeted transportation of medicines to the required region of a living organism, first of all in therapy of cancer, for contrast magnetic resonance tomography, etc.

The non-equilibrium processes of evaporation and condensation allow producing a wide range of porous condensates, which are also of interest to medicine. Non-equilibrium condensation of the vapour phase is characterised by a number of mechanisms and conditions effective for formation of porosity. One of the main mechanisms of formation of porosity is based on the so-called shadow effect. Certain geometry is formed on the condensation surface during nucleation and subsequent growth of crystallographic faces at different rates. Faces and spikes growing at a minimal rate screen the neighbouring surface regions from an evaporator (vapour flow). This results in formation of internal cavities. A porous structure is formed where the geometry caused by nucleation and growth of the second phase particles, erosion of the surface irradiated with accelerated gas ions, or chemical reactions (etching) with removal of the reaction products, is formed on the condensation surface.

Figure 10, *a*, shows microstructure of a cross section of the Ni–16 wt.% ZrO_2 ($7Y_2O_3$) condensate, 420 μm thick, produced by deposition of a mixed vapour flow of Ni and ZrO_2 (7 wt.% Y_2O_3). Zirconium oxide nanoparticles formed on the condensation surface during deposition stimulate formation of porosity with a characteristic directed (columnar) orientation.

Figure 10, *b*, shows microstructure of the porous titanium condensate 420 μm thick, produced by deposition of a mixed vapour flow of titanium and NaCl, which were evaporated from two independent sources. The deposition process was accompanied by etching of the condensation surface, first of all of boundaries of the crystalline grains, to remove (evaporate) the products of reaction $Ti + 4NaCl = TiCl_4\uparrow + 4Na\uparrow$. When jointly condensed with Al, Ti, Si, ZrO_2, Al_2O_3, TiO and SiO_2, the additions of NaCl or chlorine form easy-to-remove chlorides.

Almost all materials evaporated by electron beam can be deposited in the form of porous condensates with sizes, shapes and quantity of pores regulated within wide ranges. These are sorbents, filters, catalysts and catalyst carriers, as well as functional coatings on the surfaces of bioimplants. Further regulation of properties of porous coatings can be provided by means of capillary impregnation with a liquid phase during the deposition process or after deposition, for example, by impregnation of porous coatings on stents

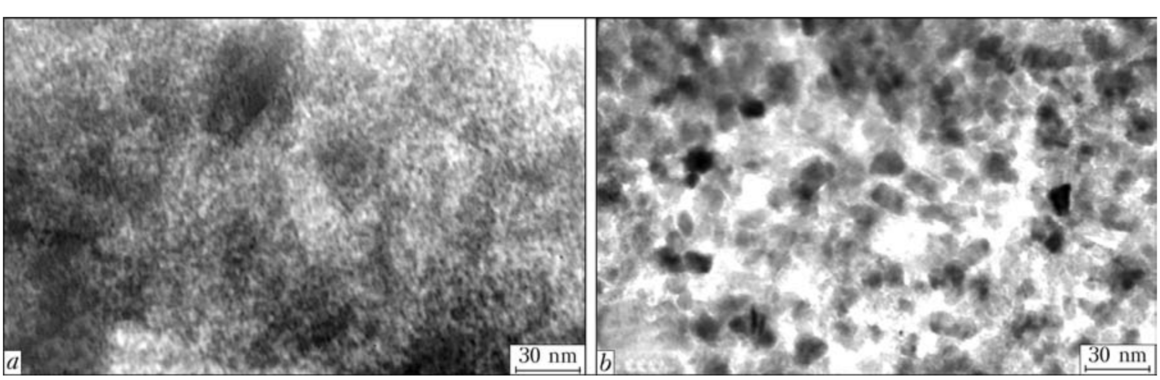

Figure 9. Mean size of Fe_3O_4 nanoparticle: *a* — 5; *b* — 15 nm

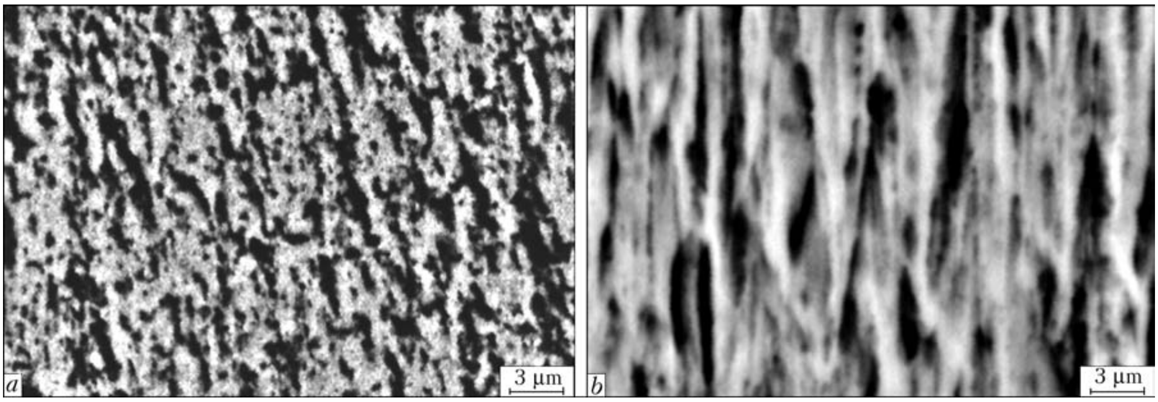

Figure 10. Microstructures of porous condensates Ni–16 wt.% ZrO_2 (7 wt.% Y_2O_3) (*a*) and pure Ti (*b*)

with a pharmacological preparation at the initial stages of introduction of a stent into an organism to suppress the inflammatory process or restenosis [31].

It should be noted that the International Centre for Electron Beam Technologies of the E.O. Paton Electric Welding Institute developed and managed production of laboratory, experimental-industrial and commercial electron beam equipment (Figure 11) to implement different variants of the technological processes of evaporation and condensation in vacuum. More than 10 units have been already manufactured for universities, research centres and industrial enterprises of USA, China, Canada and India.

The 150 and 250 kW electron beam units have a work chamber, one or two loading chambers, vertical and horizontal shafts, and appropriate manipulators to fix the substrate and workpieces.

The units have four or six electron beam guns with a power of 40–60 kW, differential vacuum system, and advanced multiprocessor system to control and monitor the evaporation and condensation processes.

This equipment can be readily adapted for research, development and commercial production of medical preparations.

Application of steam-plasma technology for disposal of medical wastes. One of the promising areas of medical application of the technologies based on welding and related processes is processing and recycling of specific wastes accumulated at health institutions. These are syringes, blood transfusion systems, bandaging materials, medical gloves, paper and plastic packing materials, napkins, biological and other wastes.

Corresponding international specifications include 45 types of the most dangerous wastes, the wastes of medical institutions heading the list. According to literature data, medical wastes formed annually in the USA amount to 3 mln t, those formed in Russia and China amount to 1 mln t, while in Ukraine the estimated amount of such wastes is about 350,000 t a year. Therefore, the problem of disposal of medical wastes is pressing and important. It is aggravated by the increasingly stringent environmental requirements to the corresponding equipment and technologies, as well as by the almost total lack of the latter. At present, the processes of incineration and burial are gradually replaced by the processes that use the energy of the plasma arc to provide a sufficiently clean disposal of the said wastes.

To solve the above problem, the E.O. Paton Electric Welding Institute in collaboration with the Institute of Gas of the National Academy of Sciences of Ukraine developed the technological process and corresponding experimental-industrial equipment to dispose of medical and other similar wastes. The process and equipment are based on utilisation of the so-called steam plasma, where the water steam is used as a plasma gas, thus providing a number of technological advantages [32, 33].

Estimation of the efficiency of the disposal process shows that implementation of the offered technology will allow a high-efficiency recycling (close to 100 %)

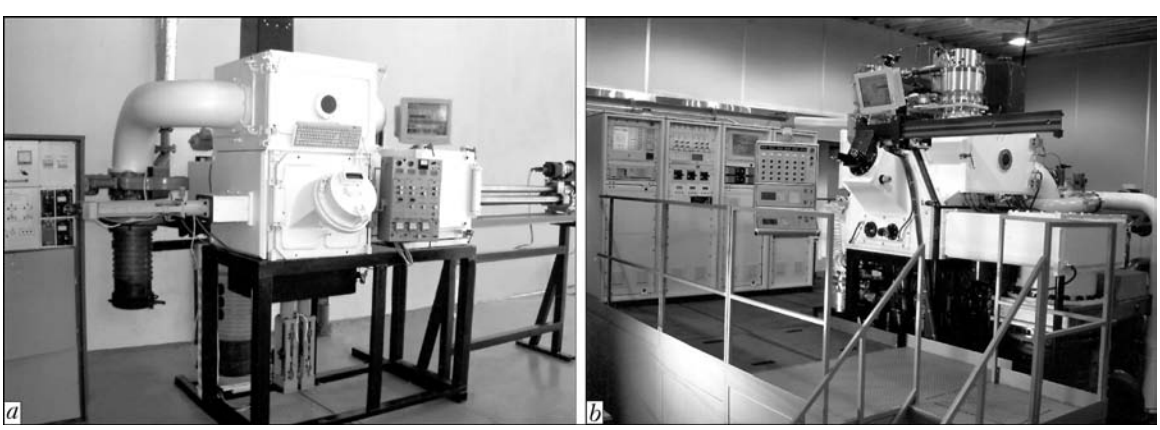

Figure 11. General view of electron beam units: *a* — laboratory unit UE-209; *b* — experimental-industrial unit UE-204

of the above type of organic wastes by simultaneously providing a target by-product in the form of synthesis gas, which is a valuable energy carrier, as well as absolutely safe solid products, which can be used, e.g. in construction industry.

Analysis shows that as a result of steam-plasma pyrolysis about one cubic metre of synthesis gas can be produced per kilo of plastic wastes (syringes, etc.), which compensates with interest for the power consumed for realisation of the steam plasma process.

Chlorine, fluorine and other dangerous elements, which are contained in many plastic materials, are fixed and thus can be easily extracted. Unlike known technologies, the products of recycling by this technology contain no resins, phenols, etc. Gasification of carbon-containing materials with water steam at high thermodynamic parameters provides the absence of sulphur compounds in the gas phase, as all the sulphur remains in a solid residue (slag). The process of plasma gasification is insensitive to the moisture content and composition of the wastes being processed.

The investigations and tests conducted are indicative of a high potential of this method. The corresponding equipment can be manufactured either in stationary or mobile version. This provides a real technical base for recycling of wastes at a site of their formation and accumulation. In addition to medical wastes, the technology can also be used to dispose of other organic wastes, including such dangerous ones as pesticides, insecticides, plastic ware and containers, car tyres, wood chips, etc. The said advantages of the developed equipment and technological process serve as a reliable basis for its promotion to the market. Demands of the Ukrainian, European and world markets (allowing for the data on the amounts of wastes accumulated by health institutions) are practically unlimited.

Therefore, one of the priority areas now is to use the capabilities of welding and related technologies to improve human health and environment. We see further prospects of development of this area. We have all reasons to believe that the collaborative efforts of scientists and specialists in the field of welding and medicine will bring much success in surgery, diagnostics, new designs of medical equipment and instruments, development of advanced materials for prostheses, and making of efficient environmental protection means.

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THEORETICAL AND EXPERIMENTAL INVESTIGATIONS OF BRITTLE FRACTURE RESISTANCE OF METAL OF WELDED STRUCTURES FOR THE ARCTIC SHELF

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Prevention of brittle fractures of welded structures of a shelf is an integrated problem, including the development of base and welding materials of high cold resistance, their certification by parameters of crack resistance and grounding of their applicability in the structure elements at a preset level of external effects on the basis of fracture mechanics approaches. To follow this path, it is necessary to solve a number of theoretical problems, connected with peculiarities of crack resistance tests of structurally non-homogeneous material of welded joints, interpretation of tests results, characterized by a large scattering, grounding of main principles of conductance of estimations. It is shown that the strength assurance by the criterion of prevention of brittle fractures requires not only the application of cold-resistant materials, but also optimizing of welding technology, updating of methods of non-destructive testing and criteria of assessment of quality of welds, as well as regulation of stress level in the structures.

Keywords: *stationary and floating drilling units, cold-resistant steels and welding consumables, brittle fracture, crack resistance, welded joints*

The exploration of hydrocarbon shelf deposits of Arctic is one of the most challenging trends in the development of fuel and energy complex in Russia. The construction of offshore sleet-proof platforms (OSPP) and floating drilling units (FDU), ice breakers and ice ships for year-round service has begun. One of the key problems encountered during development of materials for these constructions is the prevention of brittle fractures under low temperature conditions (the calculated temperature T_{cal} is down to −(50–60) °C for freezing basins and down to −35 °C for open basins). The risk of their occurrence is connected with a large thickness of structure (up to 50–70 mm for OSPP and FDU with separate elements of up to 130 mm), large length of welds, intensive cyclic wind-wave and ice loads, promoting the initiation of defects during service. In this area «Prometej» has fulfilled the following complex of works:

• cold-resistant steels, welding consumables and technological processes, which provide for the high metal resistance to the brittle fractures have been developed;

• characteristics of crack resistance of welded joint metal were investigated and correction of methods of evaluation tests for brittle fracture resistance was made;

• methods of non-destructive testing for the new class of structures and criteria of evaluation of quality of welds by the level of admissible defects were developed;

• calculation methods of predicting strength as regards to brittle fractures to ground the applicability of materials and technological processes were continuously developed.

Below, the main results of the Institute works on these trends are presented.

Development of cold-resistant materials, providing the fulfillment of Register requirements. According to the Russian Register of Shipping (RRS) [1, 2], harmonized with standards DNV, GL, ABS and other classification societies, the control of the cold resistance of metal is performed from the results of Charpy tests of specimens (KV). The regulated level of impact energy corresponds approximately to the inequality

$$KV\ [\mathrm{J}] \geq 0.1\sigma_{0.2}\ [\mathrm{MPa}], \qquad (1)$$

(here $\sigma_{0.2}$ — yield point), and the temperature of tests T_t defines the temperature category of steel (A, B, D, E, F) or welding material (1–5 categories). T_t = −60 °C corresponds to the categories F and 5.

The selection of temperature category of the material for the structure elements of cold-resistant variant is performed basing upon the principle which is expressed through the inequality

$$T_t \leq T_{cal} - \Delta T(S), \qquad (2)$$

where T_{cal} is the calculated (minimum) service temperature; ΔT is the temperature reserve, which increases with the growth of category of responsibility of structure element and its thickness S.

For the most critical sub-assemblies the requirements of standard documents correspond approximately to the condition: σT [°C] = S − 15mm. It means that materials of these sub-assemblies, positioned above the waterline, should correspond to the temperature categories F (for the base metal) and 5 (for the welded joint), whereas at S > 25–30 mm it is even insufficient. In these cases the additional proves of material applicability are required. According to [2], for this purpose the results of certification tests on the RRS programs, which are fulfilled in receiving the certificate on the approval of rolled sheet metal, welding materials by the manufacturer or in certifi-

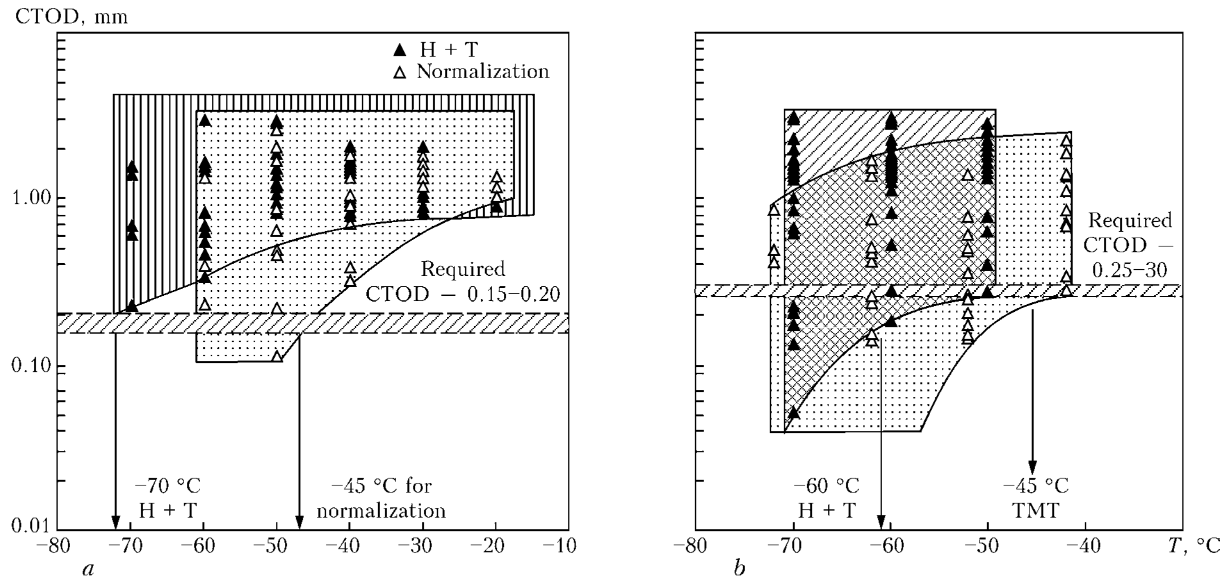

Figure 1. Results of determination of crack tip opening displacement (CTOD) for cold-resistant ship hull steels E36–E40 of 30–40 mm thickness (*a*) at normalization and temper hardening (H + T) and 41–50 mm thickness (*b*) at TMT and H + T

cation of welding procedures at the plant, responsible for construction, are used. They include crack-resistance tests using fracture mechanics methods: determination of CTOD parameter for the base metal and metal of welded joints, and also results of control of tough-brittle transition NDT (temperature of null ductility, defined at impact loading of specimens with a brittle surfacing) and T_{sp} (the temperature of appropriate 70 % fibrous constituent of fracture of full-scale sample) for the base metal.

Nowadays «Prometej» has developed the hull steels of higher weldability of *F* category with the yield point from 320 to 690 MPa and they are implemented in industry. The steels have been produced using thermomechanical treatment (TMT) and thermal hardening [3]. Due to their high-dispersed structure and low content of non-metallic inclusions they meet actually the requirements to impact energy (1) of down to –100 °C, and RRS requirements to CTOD — down to – 40 – 50 °C (Figure 1). The welding consumables such as electrodes, wires and fluxes have been developed [4, 5]. The meeting of requirements to KV at –60 °C is attained by the limited content of sulphur, phosphorus in the welding wire and raw components (in the welding wire of not more than 0.012 and 0.015 wt.%, respectively), low content of oxygen in weld metal, application of complex modifiers and deoxidizers in the content of electrode coatings and fillings of flux-cored wires, and also agglomerated fluxes of high basicity with adding to their composition of ferroalloys and metallic materials for microalloying and deoxidization. However the tests have shown that the meeting of appropriate requirements to characteristics on CTOD for the welded joints metal occurred to be the more complicated problem than keeping the requirements to KV. In this case the result depends greatly on a number of factors, defined by choice of tests procedure, and the data scattering, typical of extremely low temperatures, hinders their interpretation.

Investigation of characteristics of welded joint metal crack resistance and development of methods of evaluation of CTOD tests. The application of parameters of non-linear fracture mechanics (NLFM) for the certification of material and prediction of strength of shelf structures is due to the high level of residual welding and service stresses, the probability of brittle fractures of structure with a defect at the area of nominal elastic deformations should be excluded completely. During testing of welded structures the preference is traditionally given to such deformation parameter of NLFM as CTOD and its critical value δ_{cr}. Until now the only guideline for this type of tests for the non-heat-treated welded joints was BS 7448 standard [6].

In accordance with the RRS Regulations the CTOD tests are performed in evaluation of sheet rolled metal (so-called steel weldability control) by making a notch in metal of heat-affected zone (HAZ) of welded joint with a square edge of the weld, and also during the evaluation tests of welding procedures (in this case the joint is tested which is performed by a standard technology, the notch is made in weld metal, fusion line and HAZ). The tests are carried out at $T_t = T_{cal}$. In compliance with the requirements [2] worked out together with «Prometej», the applicability of material at the given temperature has no limits at

$$\delta_{cr} \geq \eta\sigma_{0.2}S/E, \qquad (3)$$

where E is the modulus of elasticity.

For the metal of welded joints of the most responsible and loaded structure elements the coefficient η is equal to 1.35. The given level at $\sigma_{0.2}$ = 360–450 MPa is close to standard requirements of Canada [7], and also DNV and API standards for underwater and onland pipelines of higher operational reliability.

The tests have shown that data on CTOD of metal of welded joints are characterized by a large scattering as compared with the base metal (Figure 2). At low temperatures the probability of brittle fractures of

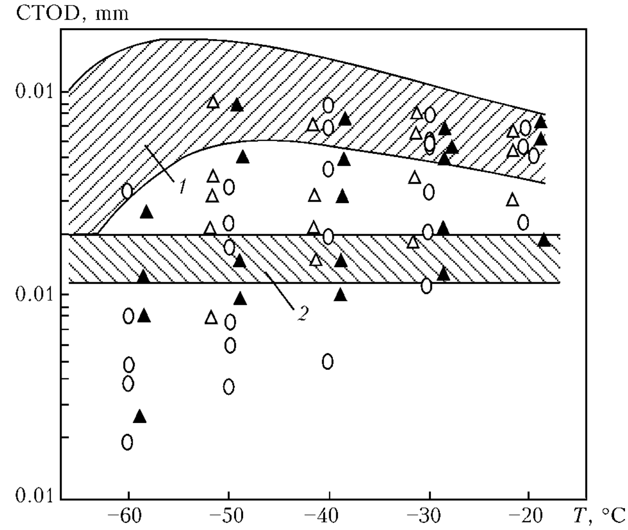

Figure 2. The results of CTOD determination for HAZ metal of ship hull steels E36–E40: ○ — coarse-grain component, welding heat input $w = 3.5$ kJ/mm; ▲ — the same, $w = 0.8$ kJ/mm; Δ — zone of a partial recrystallization, $w = 3.5$ kJ/mm; *1* — base metal data scattering; *2* — CTOD requirements

single structures of structurally-heterogeneous metal is high even at application of most cold-resistant materials. This causes the strong influence on the result of tests of procedure of their conductance: selection of local (purposeful) structure, where the crack front is located, the criterion of correction of tests for proper finding this structure (the minimum percentage of accuracy is required), crack orientation in weld metal tests, technological processes of welding, which do not deteriorate HAZ metal test results. At final evaluation of test results the conclusion about minimum CTOD value appeared to be impossible. Therefore, it is necessary to test statistically a large amount of specimens with next statistic processing of data.

The results of investigations in these trends are given in [8]. It was found that the most common variant for statistic processing of data on crack resistance is the representation of integral probability of fracture P in the form of three-parameter distribution of Weibull:

$$P = 1 - \exp\left\{-[(\delta - \delta_{c\,min})/(\delta_{c0} - \delta_{c\,min})]^b\right\}, \quad (4)$$

where δ_{c0} is the scale parameter; b is the form parameter; $\delta_{c\,min}$ is the minimum CTOD.

For the base metal $b = 2$, that is coordinated with a representation about relation of probability of brittle fracture with a «process zone» volume at the crack apex. For the metal of welded joints the b value is varied from 1 to 2, moreover, $b \approx 1$ in testing HAZ with K- shaped edge preparation of a weld and crack location in the zone of a coarse grain component of HAZ at the fusion line, that corresponds to dependence of fracture probability not on the volume but on the surface of «process zone».

The statistic processing of obtained results allows revealing the factors, which define the probability of brittle fractures of HAZ metal. The most critical is the content of coarse-grained HAZ component on the front of a crack of more than 15–20 % (Figure 3). Here δ_{c0} does not depend on the method of production of sheet rolled metal and is defined mainly by the welding heat input. As a result of selection of heat input and optimizing the weld beads layout it is possible to attain also high characteristics on CTOD for this zone (Figure 4).

The application of modern cold-resistant welding consumables provides mainly the meeting requirements of Register on CTOD at crack location in weld metal at −40 – 50 °C (Figure 5). However, in connection with the structural anisotropy of metal along and across the welding direction and structural heterogeneity in the welded joint section the test result depends on the notch orientation (along the weld or perpendicular to the surface), and also on the fraction of recrystallized dendritic structure on the front of a crack (Figure 6), that indicates the necessity of limitation of welding heat input for critical structures in a cold-resistant performance. The data of testing specimens with a notch along the weld (the crack propa-

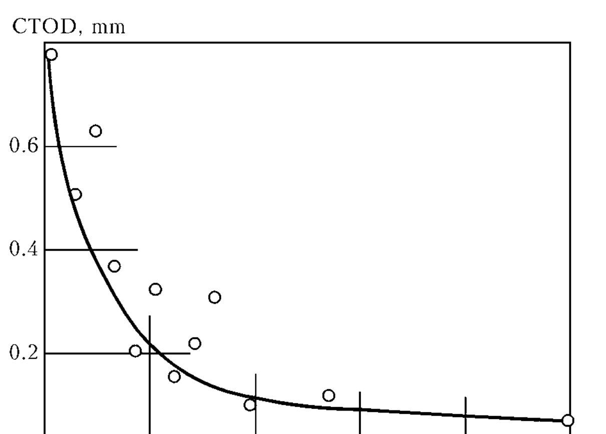

Figure 3. Dependence of mathematical expectation of CTOD on relative content of a brittle component z/t in HAZ metal of steels E36–E420: z — length of zone of a coarse-grain component; t — length of a crack front

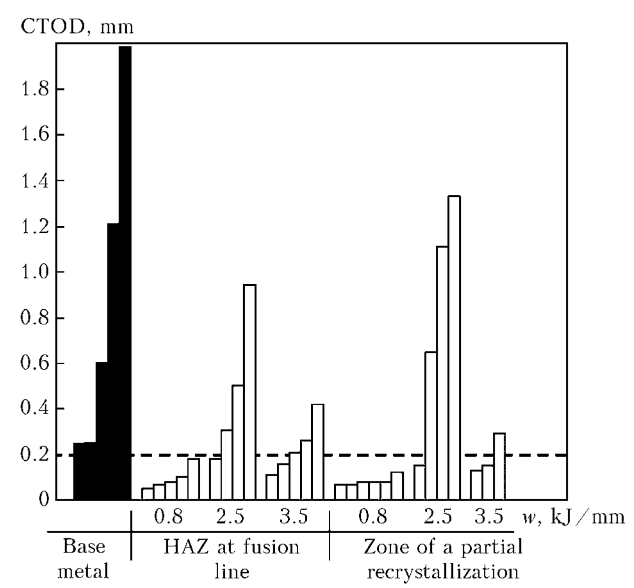

Figure 4. Dependence of CTOD on heat input of welding w obtained for steel E40W of 60 mm thickness, produced using TMT: dash line — requirements of RRS

gated normal to the surface) depend greatly on weld root zone properties and can be both much higher, and also lower than those obtained in crack propagation along the weld.

It is necessary to note that none of existing standard documents specifies the selection of specimen type and other important factors during certification tests on CTOD, leaving it at discretion of the tests customer. In this connection, the Institute has developed the procedure, approved by Register, making the important additions to the standard [6] concerning the specifying of selection of type of specimens, their preparation, criteria of correctness of tests, procedures of statistic processing of data.

Correction of NDT procedure. To improve the reliability of shelf structures at the stage of construction the Institute has developed the working documentation «Quality control of welded joints of structures of OSPP and FDU», which differs from similar standards for the ship hull structures by more differentiated approach to regulation of admissible defects, accounting for the category of responsibility of a structure member under consideration, its cyclic load intensity, group of complexity of manufacture. During the ultrasonic testing, which is main for these structures, a criterion of quality evaluation by equivalent area of a single or total defects was added to the regulation of a conditional extension of defects. This allows relating the results of testing and its parameters (rates of search sensitivity) to procedures of strength evaluation by the criterion of prevention of brittle fractures.

The above-mentioned documents have passed tests in construction of the first offshore sleet-proof platform «Prirazlomnaya» at Severny machine-building enterprise.

Development of calculation methods of brittle fracture prediction. The aim of calculation is to check the acceptability of design solutions and specifying the probability of application of materials and technological processes on the basis of tests results on crack resistance. In connection with the main NLFM postulate, the strength condition is an inequality

$$J \le J_c / n, \quad (5)$$

where, J-integral values are defined accounting for the interaction of fields of residual welding and operational stresses; J_c is its critical value (parameter of crack resistance of material), connected with CTOD formula

$$J_c = m\sigma_{0.2}\delta_{cr},$$

where m is the numeric coefficient, $m = 1-2$; n is the safety coefficient.

To define the calculated J value the method «Failure Assessment Diagram» [9] was applied, where the fracture surface, corresponding to the condition J = = const, is described by the function

$$J = J_{el} / f^2, \quad (6)$$

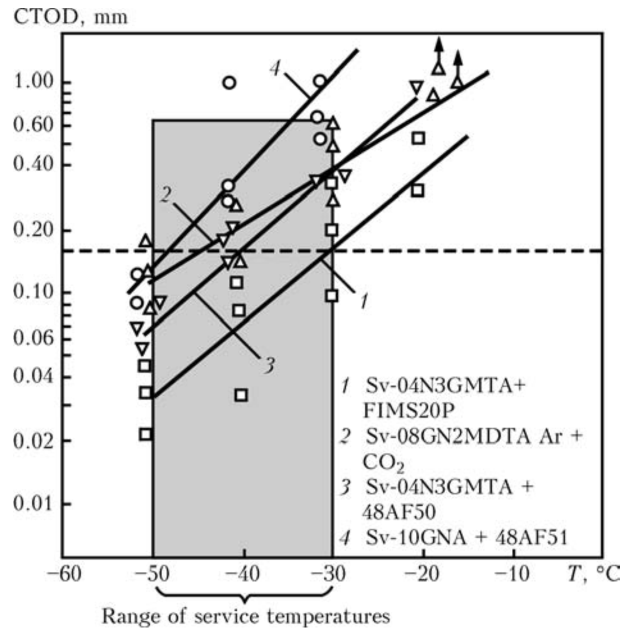

Figure 5. Results of determination of CTOD for weld metal with a crack in weld center (fracture — along the welding direction): dash line — level of RRS requirements and foreign societies by CTOD parameter

where $f = (1 - 0.14L_r^2)\ [0.3 + 0.7\ \exp\ (-0.65L_r^6)]$ («R6»procedure); J_{el} is the elastic component of J; L_r is the relation of load to limited one corresponding to the exhaustion of load-carrying ability.

In the scope of this approach the method of account for interaction of residual and operational stresses (the summing up of elastic J-integral components, defined for residual J_{el}^r and operational J_{el}^d stresses at low loads) and partial relaxation of the first ones at high loads have been specified:

$$J_{el} = J_{el}^d + J_{el}^r(1 - 0.67L_r). \quad (7)$$

The J_{el}^r values are determined applying formulas, interpolating the results of numerous FEM solutions

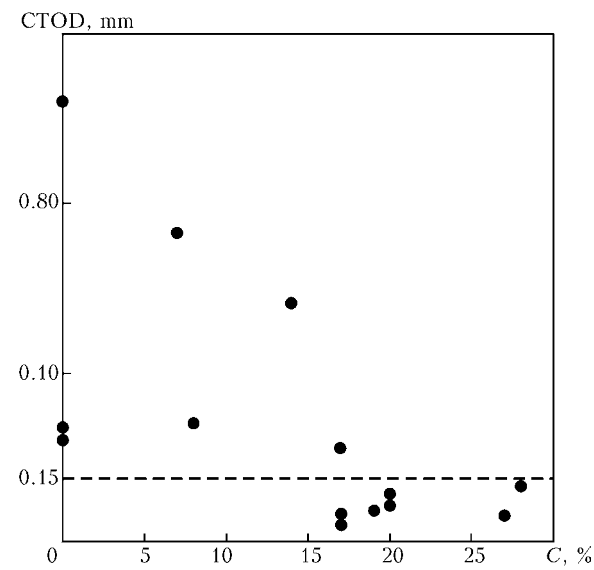

Figure 6. Change in CTOD of weld metal made by the automatic welding (Sv-10GNA + 48AF53), depending on enter of crack front into non-recrystallized structure: C — fraction of a non-recrystallized structure; dash line — requirements of RRS

of thermodeformational «welding» problems, modeling the stressed state of welded joints with crack-like defects.

The main problematic moment in conductance of these calculated evaluations is the selection of dimensions of a calculated defect, purpose of a safety coefficient and confidence probability due to which the material crack resistance should be defined. Here, the principle mutual coordination of these parameters was applied so that to make the calculation result corresponded to the preset probability of brittle fractures, close to 0. This condition may be formulated in the following way: in calculation of the brittle strength in the deterministic statement the fulfillment of inequality

$$J_c/n - J(a, c) < 0 \tag{8}$$

should mean that probability of inequality fulfillment

$$J'_c - J(a') < 0 \tag{9}$$

is ensured at the required level, for instance equal to 0.001, for the most critical situations. In the condition (8) the average J_c value is considered defined from results of the tests, and the dimensions a, c of a calculated defect correspond to the area of a defect, 10 times exceeding the preset search sensibility in ultrasonic testing (UST) — $a:c = 2/3$. In the condition (9) J'_c, a' are the random values of J_c and a, chosen in accordance with preset laws of distribution of these parameters. For the stationary condition of loading the parameter a should be considered as the only random factor which defines J value; at the non-stationary temperature-force condition, typical of the offshore engineering structures, operational stresses, defining J, and the temperature of their realization influencing J_c, are also random.

For the numerous investigations of conditions of inequality (8) fulfillment, the method of Monte-Carlo and found ways of statistic processing of experimental data of functions of distribution of parameters of crack resistance and maximum defect dimensions in the preset volume of metal, revealed after 100 % UST, were used. The result of calculations was the determination of relation of probability of structure element fracture with parameters of statistic distribution of crack resistance at minimum (calculated) temperature of service. This allows the definition of safety coefficient values (8), accounting for a real scattering of data. For the welded joint metal of the most critical subassemblies the n values, hereby defined, made up 8.5 for the stationary and 5.0 for non-stationary load.

The above-mentioned methods found their application in analysis of reliability of upper structures of OSPP «Prirazlomnaya». According to the evaluation results the volume of non-destructive UST was recommended for the most loaded structure elements. The application of these methods is especially rational in use of high-strength ship hull materials, materials of thickness of more than 50 mm, and also in the situations connected with the determination of admissible conditions of construction service.

The challenged research areas. The results of carried out research works have showed the necessity in continuing works, connected with the increase in fracture toughness of welded joint metal at temperatures lower than −40 °C. This is really actual for welding thick metal, high-strength steels with the yield strength of up to 690 MPa, and also applicable for the constructions, located in the coastal and inland basins of Artic, where the expected calculated temperatures may reach −60 °C. In case of application of conventional types of electric arc welding the prospects of further works in this area are envisaged by the Institute with the application of modifiers in the form of nanoparticles, added to the composition of fluxes and electrode coatings. The challenged trend of works is implementation of laser welding for construction of offshore structures. The preliminary research works on serviceability of butt joints of cold-resistant steels, produced by this method of welding, showed the opportunity in achieving the high characteristics of impact energy KV and on CTOD. At the speed of welding about 40 m/h under condition of a spike penetration the weld metal meets the requirements on KV at the temperature of down to −60 °C, on CTOD — at down to −40 °C.

Thus, the problem of prevention of brittle fractures of welded joints of offshore constructions for the Arctic shelf requires the performance of works in several trends, namely: development of cold-resistant welding consumables, optimization of welding technology, improvement of methods of control of actual resistance of structurally-heterogeneous material to brittle fracture, establishment of grounded more strict criteria of admissible defectiveness and control of admissible loading of structure on the basis of check-out evaluations of strength. The works on above problems, carried out over many years in «Prometej», allowed the creation of the first sleet-proof platforms using national materials and solution of the current tasks of their designing and construction. The actual is the further carrying out works on the development of technological processes providing the precise fulfillment of criteria of prevention of brittle fractures at down to −60 °C temperature in welding of cold-resistant thick steels and high-strength steels.

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IMPROVING THE GLOBAL QUALITY OF LIFE THROUGH OPTIMUM USE OF WELDING TECHNOLOGY

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This paper gives an overview of the work of IIW internationally, in various regions of the world and industry sectors utilising welding, the challenges being faced, opportunities available, and probable requirements for the successful introduction and optimum use of welding technology. Successful models used in other countries, particularly for technology diffusion to industry, education and training, improving the image of welding and the use of appropriate technologies will be highlighted. The involvement of industry and governments across the world in conjunction with the work of IIW and its 52 member countries, particularly the involvement of the Ukraine, is critical to the success of such initiatives.

Keywords: *quality of life, welding technology, International Institute of Welding*

The International Institute of Welding (IIW). The IIW was founded in 1948 by the welding institutes or societies of 13 countries, who felt the need to create it, to make more rapid scientific and technical progress possible on a global basis.

Since then, welding associations in 52 countries make up the members and more and more are indicating interest. There are now 15 members in Western Europe, 11 in Eastern Europe, 6 in the Americas and 20 in Africa/Asia/Oceania.

From the beginning, the IIW set up international groups of specialists to study collectively the scientific phenomena associated with welding and allied processes, their more efficient industrial application and the means of communicating information about them. It has therefore become the global body in the science and application of joining technology, providing networking and knowledge exchange as part of its mission.

Its mission is to «Act as the world-wide network for knowledge exchange of joining technologies to improve the global quality of life».

Henry Ford, the great American philanthropist and car maker, said: «You can do anything if you have ENTHUSIASM. Enthusiasm is the yeast that makes your hopes rise to the stars. Enthusiasm is the sparkle in your eyes, the swing in your gait, the grip of your hand, the irresistible surge of will and energy to execute your ideas. Enthusiasts are fighters. They have fortitude. They have staying qualities. Enthusiasm is at the bottom of all progress. With it there is accomplishment. Without it there are only alibis».

With enthusiastic leadership, IIW can truly make a global contribution.

Welding technology is an enabling technology used across a wide range of industries and applications. These range from micro-joining of medical devices, electronics and photonics (down to 5 μm), to larger scale applications such as bridges, buildings, infrastructure, offshore structures, defence equipment, mining equipment, boilers and pressure vessels, piping, ships, rail and road transport, water and gas pipelines, nuclear, and including components over 1 m thick welded in one pass. All these industries and others exist in all countries to varying degrees, thus creating a significant use of welding technology. Welding and joining is used widely in the manufacture of most consumer products.

Welding's value to a nation's economy is significant as shown by recent detailed studies in countries such as the USA [1] and Germany [2].

This critical technology encompasses the total lifecycle of welded products/structures including design, manufacture, conformity assessment, inspection and testing, operation, maintenance, repair and decommissioning including recycling and other environmental considerations.

Objectives of IIW. IIW has just undertaken a major review of its business plan involving all of its working and administrative units.

Some key IIW objectives, amongst others are:

- identify, create, develop and transfer world's best practices;
- identify, develop and implement the IIW Education, Training, Qualification and Certification (ETQ&C) Programmes on a global basis;
- promote IIW, its member societies and services in various regions of the world to the mutual benefit of all;
- implement the IIW's outcomes;
- provide quality services to IIW members and other organisations.

To achieve these objectives in practice, experts from around the world are voluntarily working in 15 Commissions, 6 Select Committees, 2 Study Groups and a host of Working Groups or other units on a permanent basis to stimulate and co-ordinate research and technology diffusion, and to diffuse information on welding technology, its application in terms of materials, processes, design and inspection and other associated subjects such as health and safety, education, training, qualification and certification, terminology and documentation.

Structure of the IIW. *Administrative Structure*. The policies of IIW are decided by the General Assembly at which are represented all the national member societies. The General Assembly elects the President of IIW and the members of the Board of Directors which directs the affairs of the IIW. The Board of Directors comprises twelve Directors among whom are elected the President, three Vice-Presidents and the Treasurer. Countries currently represented on the Board in 2007/2008 include Australia, Austria, Croatia, China, France, Germany, India, Japan, Portugal, Singapore, Sweden, United Kingdom and the USA; a good geographical balance between countries.

The day-to-day work is ensured by a four staff member permanent Secretariat based in Paris. Under the responsibility of a Chief Executive, the Secretariat includes a Scientific and Technical Officer, a Standardisation Officer and Secretarial Assistant. The CEO since 2000, Mr. Daniel Beaufils retired in January 2008 after eight years of excellent service and has been replaced by Mr. Andre Charbonnier.

The Secretariat also maintains contact between IIW and other international bodies such as the International Organisation for Standardisation, United Nations agencies and others.

The Board of Directors has a Technical Management Board (to which over 20 working units report), as well as three other Working Groups; Communications and Marketing, Regional Activities and Liaison with Developing Countries and Standardisation reporting to it.

The IIW, a not-for-profit body, is funded by the member societies paying an annual subscription on a scale designed to reflect, as equitably as possible, the dependence of their country on welding technology. Such subscriptions are modest and sufficient to pay only a part of the cost of running the Secretariat and associated activities. Further income is derived from the sale of books and other documents, and fees which are collected from each Annual Assembly participant.

By far the greatest contribution from member societies comes in the form of the input of their delegates to the working programmes of the Commissions. The cost of delegates attendance at Annual Assemblies and any intermediate meetings of Commissions and Sub-Commissions are borne by their Member Societies or the delegates' employers.

Throughout the life of IIW, the scope of its technical programme has been continually expanded to include new technologies. Such have included more recently, the joining of plastics and composites, the capabilities of computers in design, process control, inspection and information handling, welding in a variety of environments and under remote control, new concerns for the health and safety of those working in industry and the education, training, qualification and certification of personnel and companies.

The Institute, in July 2007, finalised its new Business Plan involving all administrative and working units to ensure ownership by all participants over the 2008–2012 period.

International Authorisation Board (IAB). An important innovation of the IIW was the formal establishment in 1999 of an international programme for the qualification of personnel involved in welding operations. Through the IAB, this scheme allows the IIW Authorised National Bodies (ANBs) in member countries to deliver, under the control of the IIW, Diplomas of International Welding Engineers (IWE), Technologists (IWT), Specialists (IWS), Practitioners (IWP), Inspectors (IWI) and Welders, amongst others. The Diploma holders for IWE, IWT and IWS are de facto recognised as able to be Responsible Welding Coordinators according to the Standard ISO 14731 «Welding coordination — Tasks and responsibilities».

Thirty-six IIW members actively participate in the IAB and through their ANBs, over 30,000 IIW Diplomas have been issued since the programmes started in 2000. The Instituto de Soldadura e Qualidade in Portugal provides the Secretariat for the IAB and its two working groups: A — «Education, Training&Qualification» and B — «Implementation&Authorisation».

With the ever-growing global use of the ISO 3834 «Quality requirements for fusion welding of metallic materials» and ISO 14731 «Welding coordination — Tasks and responsibilities» standards, more and more countries are using the IIW International Programmes.

National Delegations. People can be appointed to be members of their national delegation. The appointment process varies from one country to another but generally the main criteria are:

- to be known by the relevant national authority responsible for the appointment of the country's delegation;
- to be an expert in a subject dealt with by an IIW Commission or other Working or Administrative Unit;
- to have the motivation and energy to participate in the co-operative work of the unit which may meet not only at the Annual Assembly, but more frequently in order to maintain progress (often in Paris in January each year);
- to have an interest in working with people of other nationalities whose basic assumptions and habits of thought may well be quite unfamiliar.

For those committed to co-operation, there are many opportunities to contribute to, and learn of, work which will be valuable to them professionally and to their employers, to make the acquaintance of fellow experts from other countries, to gain, through personal contacts and technical documents, advance knowledge of impending developments and, in some cases, to influence the content of international welding standards.

Some achievements of IIW. *Technical Management Board*. The groups of experts in the Technical Commissions and other units under the Technical Management Board have achieved many outputs useful to industry, both nationally and globally.

- *Technical papers*. Each year about 400 papers emanate from the IIW working units of which about 60 are published in the IIW journal «Welding in the

World». A plan of action has been developed in order to meet the requirements of the Science Citation Index which includes the implementation of a peer review procedure for the research papers and IIW Database. In addition, a total of some 100 books dealing with recommended practices or the results of international enquiries have been published mainly in two or more languages.

• *Terms and IIW database*. IIW has compiled a number of works of reference such as the Multilingual Collection of Terms for Welding and Allied Processes (9 volumes mostly containing 16 or more languages), the International Welding Thesaurus developed over 30 years in conjunction with the TWI bibliographic database Weldasearch, the Index of Welding Standards and a collection of radiographs illustrating weld defects. More recently the IIW Database, referencing all IIW technical documents since 1950, has been made available online through the IIW website. All these works were approved for publication by international groups of experts and so are authoritative. IIW's virtual library constitutes one of the world's largest online sources of welding information available today. IIW Members can consult and share technical documents, white papers, publications and articles through a database of around 15,000 documents, of which more than 4,300 may be downloaded from the IIW web site http//www.iiw-iis.org. Bibliographic reference to documents can be searched by all visitors to the website, and hard copies acquired through the IIW Secretariat.

• *ISO support*. With regard to the objective of formulating international standards, the working units of the IIW have supplied the technical basis of the great majority of welding standards issued by the ISO over the past 35 years. Members of these working units and their employers have therefore had a major influence over the content of such standards. Since 1989 the IIW has been authorised by ISO to prepare the final texts of international welding standards as an international standardising organisation. This work is coordinated by the standardisation staff within the IIW Secretariat and an increasing number of ISO Technical Reports are being produced.

• *Promotion of national industry*. IIW has also been successful in promoting the organisation of national welding associations. Such associations have been formed with a view to their becoming members of IIW, thus enabling experts from their respective countries to participate in IIW activities. The IIW has taken steps to increase the promotion of membership in developing countries and economies in transition, which could benefit greatly from the collective knowledge of the IIW in many areas, in particular welding education and training, appropriate welding science, technology and practice, and the health and safety of welding personnel. Before becoming full members, countries can join as Associate Members. Within the same country more than one organisation can group together normally under a national council for IIW. IIW has recently amended its membership rules to make it easier for small developing countries to become members. Up to three countries with common geographical boundaries and less than 1 M tonnes of steel consumed between them can group together as one member.

• *Annual Assemblies*. IIW Annual Assemblies have been taking place since 1948 and take place on the invitation of one or other of the member countries and last for a week. Three days are normally devoted to parallel sessions of the Commissions and other working units. In addition, two days are normally devoted to an international conference on a specified theme. The papers presented at this conference are normally published in bound volumes and/or CD format available for purchase, and as a special issue of the IIW journal «Welding in the World». Generally, over 40 countries are represented by about 450 delegates at Annual Assemblies together with about 200 accompanying persons. Attendance at meetings of IIW working units is confined to those who have been appointed by their national delegation whereas the International Conference is open to any person.

Recent and future public event themes are:

2004 — «Technical Trends and Future Prospectives of Welding Technology for Transportation, Land, Sea, Air and Space». Osaka, Japan;

2005 — «Benefits of New Methods and Trends in Welding to Economy, Productivity and Quality». Prague, Czech Republic;

2006 — «11th International Symposium on Tubular Structures». Quebec, Canada;

2007 — «Welding & Materials: Technical, Economic and Ecological Aspects». Dubrovnik, Croatia;

2008 — «Safety and Reliability of Welded Components in Energy and Processing Industry». Graz, Austria.

Other specialist public events and seminars are usually held in association with the Annual Assembly.

The IIW will continue the programmes of its various working units, particularly on the occasion of forthcoming Annual Assemblies, which will be held as follows: 2008 — Graz, Austria; 2009 — Singapore; 2010 — Kiev, Ukraine; 2011 — Mumbai, India; 2012 — USA (venue to be finalised).

Regional activities and liaison with developing countries. During the 1980s, discussions took place within IIW on how the benefits of IIW could be promulgated to countries in the different regions of the world. It was felt that the three key areas by which IIW could assist regions, developing countries and economies in transition to improve the quality of life of all people were through implementing:

- appropriate welding technology;
- education, training, qualification and certification;
- occupational Health & Safety (OH&S).

To start implementing this strategy, it was agreed to hold Regional (now called International) Congresses with the following specific objectives:

• to expose delegates from industry in the host countries in the region, to the work of IIW;

• to identify the needs of the surrounding countries in the region and produce IIW supported programmes to help meet those needs particularly through the efforts of the host country;

• to have organisations such as the United Nations Industrial Development Organization (UNIDO), International Atomic Energy Agency (IAEA) and the European Union (EU) formally involved in the Congress and subsequent programmes;

• to have authors from the less developed, surrounding countries presenting papers;

• to form regional commissions of the IIW using representatives of the regional countries that could then provide input to the main IIW commissions.

These Congresses have become very popular and successful.

The IIW's first International Congress was held in Australia in 1988, followed by Brazil (1992), New Zealand (1996), South Africa (1997), Iran (1998), Australia (2000), Singapore (2002), Iran (2003), Egypt (2004), India, Israel (2005), South Africa, Romania and Thailand in 2006, and Australia in 2007, India, Brazil and China in 2008. Further International Congresses already planned include: in 2009 Iran and in 2010 Israel. A major success of these Congresses has been to assist technology development and diffusion in regions sometimes far removed from the locations of the majority of Annual Assemblies and to encourage IIW membership in developing countries in these regions. Potential future congresses include Indonesia, Vietnam, Kuwait, Nigeria, Mexico, Slovakia and Malaysia.

An important approach since 1993 has been to have a more systematic approach to regional activities with the compilation of a strategic business plan for the Working Group with the Goal «To promote IIW and its member societies to the countries in the various regions of the world to the mutual benefit of all», and four key objectives:

• to promote the holding of IIW supported events throughout the regions of the world;

• to introduce the IIW WeldCare Programme for take-up by developing countries and economies in transition;

• to continually promote and market IIW in different regions of the world;

• to harmonise IIW's efforts with other organisations' efforts in each region.

Over 20 detailed strategies support this goal and objectives.

IIW strategic plan and business plan (2007–2012). McKinsey Quarterly Web Exclusive 2006 [3] highlights some important global trends to watch for:

• centres of economic activity will shift profoundly, not just globally but also regionally;

• shifts within regions will be even more dramatic;

• today Asia (excluding Japan) accounts for 13 % of the world's GDP, while Western Europe accounts for more than 30 %. Within 20 years the two will converge.

Objective. The IIW, at its Annual Assembly in Prague in July 2005, agreed to a new approach on updating its Strategic Plan and Business Plan for the next five years.

In today's world, no country or organisation can remain in isolation with issues now becoming truly global, e.g. the ozone layer problem, Chernobyl, trade, travel, IT, climate change, etc.

Most people in the world simply wish for a decent job and roof over their heads, sufficient food, health and security for their families and a decent education for their children, and an environment in which all forms of life can exist in harmony.

Part of the vision of IIW is to have an influence in the promotion of welding technology in all countries of the world. In particular, IIW wishes to be able to grow to an optimum size whereby the necessary identified services can be provided to its members.

There are over 200 countries in the world, however, and all use welding and joining to varying degrees; 52 of these countries are members of IIW probably representing over 80 % of the developed world.

To achieve this part of its vision, IIW is now at a stage in its development where it is playing a leading role as a facilitator, through its member societies, to meet the needs of many non-member countries and at the same time improve its own image and influence on the global stage.

Now, particularly with the shifting of global industrial and population growth, the IIW is encouraging these new centres as well as those of the developing countries, to become more involved in IIW.

The main needs of many developing countries and those with economies in transition are arguably, in education, training, qualification, certification, health and safety as well as the introduction of appropriate technologies to be customised for use in their industries.

IIW Project «To Improve the Global Quality of Life through the Optimum Use of Welding Technology». If one considers all the attributes of an organisation such as IIW, a key challenge is how to utilise these attributes to achieve the above Project objective. This Project, approved by the IIW Board of Directors in July 2005, can dovetail many of the IIW activities (including those of its member societies) that are taking place to everybody's mutual benefit. A few of which could be important to different world regions, are discussed below.

IIW regional activities and the IIW WeldCare Programme. In many developing countries numerous geo-political and socio-economic problems hold back their sustainable development in a sustainable environment. Also their science and technology attributes have struggled to develop for a myriad of reasons.

This programme was initiated in 1994 when IIW President Raul Timmerman, Vice President Chris Smallbone and Head of the IIW Technical Secretariat, John Hicks approached UNIDO representatives for support for such a programme [4]. The model was based on the South African Institute of Welding (SAIW) which grew from a part-time secretary in 1977 to a full time staff of 49 in 1989, based in a fully owned 3500 m^2 specific purpose building [5]. The concept of having educational support centre networks and technology support centre networks grew from this model [6]. With 7 full-time technical consultants, 14 full-time lecturers and instructors, it operated throughout Southern Africa uplifting the quality of life of millions of people. From 1980 to 1989 it introduced more types and levels of world class personnel qualification and certification programmes than any single organisation in the world has ever done. These still operate successfully today and, where applicable, have been converted to international programmes. UNIDO was quite enthusiastic to support the programme for the rest of Africa. Unfortunately the UNIDO support fell away due to personnel changes in UNIDO but has recently been renewed.

Some success did arise however, through the International Atomic Energy Agency (IAEA). Initiated by SAIW in 1992, since 1994 the IAEA has supported parallel NDT training and qualification for the whole of Africa, conducted at the SAIW.

Over the past 20 years, many examples can be given of projects where IIW member countries have assisted both member and non-member countries to improve their welding technology and hence quality of life.

Consider the following example amongst many others: Germany–China; France–Thailand; UK–Malaysia; USA–Trinidad and Tobago; Japan–Vietnam; Portugal–Angola; Japan-Egypt (Africa); Austria–Indonesia; South Africa–Africa (IAEA); Germany–Vietnam; USA–Nigeria; Holland & Canada–South Africa; Australia–South Africa; Germany–Indonesia.

The main emphasis on all the above examples was on education and training and appropriate technologies. The E.O. Paton Welding Institute has trained welding engineers in many developing countries during the past 40 years.

IIW is actively cooperating with aid agencies to expand these types of projects through its IIW Weldcare Programme. Discussions are taking place with agencies such as IAEA and UNIDO on welding technology training for different levels and types of personnel throughout Africa. Such programmes were first recommended back in 1992 with a joint team effort by WTIA, ESKOM and the SA Atomic Energy Agency (AEA) initiating IAEA NDT training still being supported today [7]. This was based on the successful IAEA South American model. Such programmes could also be implemented in some of the regions of the world currently being targetted by IIW, e.g. Western Africa, South East Asia, and Gulf Region.

IIW has tremendous strength in its member countries. Its member societies have resources to assist in establishing within a particular country or region:

- an organisation that would be responsible for the promotion of welding technology and related disciplines;
- the required welding education and training infrastructures;
- the appropriate technologies to assist the different industries being established and able to be self sustaining in a sustainable environment.

A proper business plan for each country would need to be devised however, financially supported and implemented with appropriate milestones and key performance indicators. IIW is assisting countries with a model business plan and strategic plan.

Depending upon the geographic size of the country, its industrial size and distribution, a practical action plan to suit the specific needs of the country should be possible.

Education, training, qualification and certification — IIW Educational Support Centres Networks. Culture is «A way of life or life style summarised in a system of particular values and attitudes which result in characteristic actions and customs». There are three key cultures that help make a country, company or individual successful.

A skills culture is a national way of life which is characterised by:

- support of, and value placed on, a willingness to learn;
- respect for people who acquire skills;
- tangible rewards for individuals who acquire skills.

This means that people at all levels and in all disciplines in organisations will have a willingness to adapt or learn new skills. They will also be seen to deliver excellent work results. Organisations will be seen to promote skills development and will be highly productive and competitive. All of the above will lead to a thriving national economy since a culture of skills development is encouraged nationally.

A quality culture where companies with the correct culture in quality automatically:

- introduce quality management systems;
- provide service quality;
- improve performance and productivity;
- cut costs and improve profits;
- give clients confidence in the reliability of products;
- give clients confidence that the orders will be right first time on time.

A productivity culture is about the ability that a system (be it an individual, a department, a business or the economy) has, to use all the resources at its disposal in a collective sense to provide products and services which are useful to the end user. Productivity improvement is the improvement of that ability. A productive culture is where everybody and every effort contributes to improving and building up themselves, the economy and the nation.

Through IIW Commission XIV «Education and Training» as well as the member countries in the IIW

IAB, all 52 IIW members are involved in education, training, qualification and certification of personnel and many with the certification of companies — all contributing to a skills culture in the welding industry.

This has enabled IIW to establish an international network of educational/training support centres into which any non-member country can dovetail. A similar network could become a greater reality in any country or region with the national IIW ANB(s) coordinating it. Excellent working national models exist in countries such as Germany and Australia with the German model being outstanding. South East Europe is currently introducing a model between six to nine countries.

Training is a most powerful way for national improvement. With the increase in global trade, the need for product conformity assessment and the ever increasing number of product or application standards specifying ISO 3834 and ISO 14731, there is growing demand for international approaches to personnel qualification and certification, as well as certification of companies.

In Prague, in July 2005, the IIW Board of Directors resolved to introduce IIW certification programmes already introduced by the European Welding Federation, amongst others. These include :

- certification of International Welding Engineers, Technologists, Specialists;
- certification of companies to ISO 3834 Quality requirements of fusion welding of metallic materials;
- certification of companies on Occupational Health and Safety Management;
- certification of companies on Environmental Management;

The first two above were launched in Croatia at the 2007 IIW Annual Assembly and the latter two should follow in due course.

The introduction of an IIW certification programme for welding inspection personnel is currently under discussion.

IIW technology support centres network. A key IIW strategy is the promotion of the concept of innovation through technology diffusion which can be defined as:

- identifying and analysing the needs of industry in a country or company;
- sourcing solutions to meet these needs;
- disseminating the technology and information into companies, particularly SMEs and micro-enterprises;
- adopting, adapting and implementing by technology receptors of new technology/information;
- improving performance of the companies and measuring the value of improvements;
- providing feedback for further national or company improvements at each stage of the technology diffusion process.

In any country, at least 97–98 % of information/knowledge required is readily available from other countries' sources; technology diffusion is more important to many countries than conducting research.

IIW member societies with a well developed infrastructure can easily access and utilise the outcomes of the IIW Technical Commissions and working units to improve innovation in their countries. Developing countries and those with economies in transition may need to utilise a different approach or concept to suit their particular condition.

IIW has investigated and developed other models for different types of countries. It has held a number of Technology Innovation workshops in IIW member countries including India, Greece, Bulgaria, Romania, Serbia and South Africa.

In Australia, the WTIA has established a very successful model entitled «OzWeld Technology Support Centres (TSCs) Network» [8] which has further expanded to the «SMART TechNet» project. The South East European countries including Romania, Bulgaria, Croatia, Macedonia, Serbia, Turkey, Greece and Montenegro are now working together to implement a similar TSCs network between their countries. The first day of the three-day IIW International Congress for the South East European countries from the 26–28 May 2006 in Timosoara, Romania, was dedicated to a Technology Innovation workshop discussing the implementation of such a model.

UNIDO, IAEA, the EU and the Department for International Development (DFID) in the UK agreed to give presentations and work together with IIW member societies to investigate the correct way forward for the region.

In January 2007, a two-day workshop was held in Belgrade to move the concept further along to be followed by a further workshop in Athens in January 2008.

A key outcome could then be IIW member societies working with the aid agencies mentioned to facilitate projects in a variety of regions around the world, e.g. Southern Africa, South East Asia, West Africa and South America.

A combination of the models in 5.2.2 and 5.2.3 is presently being promoted as an ideal model [9]. This could also be used nationally in many countries such as India, China, Brazil and Indonesia.

Improving the image of welding. A common complaint amongst IIW member societies is the poor image of welding, with the general public, governments and general industry, but particularly with young people, leading to their lack of interest in careers in the welding industry. Some countries such as the USA and Germany have initiated national campaigns and even countries such as Japan, which has had an excellent record in welding technology, are also facing problems in this area.

The IIW is now studying how an international approach through IIW and its member societies can be implemented. When one considers how modern society depends so much on welding technology, it is quite amazing that one still has to continually «sell» the technology. The value of welding and its contribution to daily life are not appreciated by many sectors of society.

How could people survive without services such as transport and water, products such as computers, mobile phones, artificial hearts, bionic ear implants, etc, etc, etc? Where do the global and individual benefits end? Whether a high pressure gas pipeline extending thousands of miles across Australia or a pipe supplying water to a village in Africa, welding technology makes a huge positive impact on the global quality of life. Its value to a nation's economy is both significant and critical as shown by studies in countries such as the USA and Germany.

16 strategies on improving the image of welding have been implemented in the sections of the IIW Business Plan involving the IIW Board of Directors, International Authorisation Board (IAB), Working Group Regional Activities and Commission XIV.

IIW White Paper or White Book. One important strategy that is part of the project is for IIW to compile a «White Paper» or «White Book» on welding and joining technology [10]. Such a document is to be used on an international basis and aimed at decision makers in governments, industry, research and development, academia, education and training, amongst others, to assist them in their welding related areas of interest or influence.

The IIW has formed a White Paper Task Group consisting of 12 prominent members of the global world of welding and more than 40 international experts are contributing to the document.

For example, it could:

• influence governments and industry on the R&D needs, magnitude and types of research funding to be made available;

• improve the image of welding and its importance to both the national, regional and global economies;

• guide industry on future types and numbers of personnel requirements;

• provide technological developments including «hot topics»to improve the global quality of life;

• raise the national and international profile of IIW and its member societies.

The title of the «White Paper» is linked to the title of the IIW Project «To Improve the Global Quality of Life Through the Optimum Use of Welding Technology». It will have the following five objectives amongst others:

• to identify the challenges for welding and joining technology in the global arena;

• to recommend the implementation of strategies to find solutions to meet these challenges;

• to agree on solutions for the next 20 years;

• to promote the implementation of identified solutions on a national, regional and international basis through greater collaboration, shared knowledge and partnerships;

• to improve overall global quality of life, i.e. health, safety, food, water, fair trade, environment, education opportunities.

Potential regions of cooperation. The welding industries in all world regions are facing some exciting challenges over this next decade particularly due to the forecast in global growth and it being evident that vast amounts will be spent on infrastructure projects alone, with enormous economic growth taking place in countries such as China, India and neighbouring countries.

Industry sectors involved in such projects, and all involve welding technology, include road, rail, water, transport, power generation, petro/chemical, nuclear, pipelines, oil and gas offshore amongst others. Such projects also enable countries to improve the quality of life of their people whilst at the same time protecting the environment both nationally and internationally. This is so important since «no man is an island» as has been shown by disasters such as the failure at the Chernobyl Nuclear Power Plant in the Ukraine or lately the problem of climate change.

The geo-political and socio-economic challenges of countries have been well documented. How does an organisation such as IIW and its member countries try to assist countries further to improve their quality of life? Examples have been given previously [11–22].

The variety and magnitude of the challenges facing countries as well as the resources to meet the challenges probably vary from country to country.

In terms of the welding industries to be involved in infrastructural projects, as well as the normal fabrication, construction and maintenance work that happens on a daily basis, the IIW is confident that there are many areas in which the national welding associations can work together with IIW for the common good.

The first step in finding a solution would be to continue to promote greater regional cooperation and greater involvement in IIW by regional country representatives.

International organisations such as UNIDO, EU, DFID (UK) and IAEA could channel projects through IIW, these countries and the regions.

The IIW Member Societies in the different world regions are prime players in welding education, training and technology transfer, and with adequate resources, could all play a bigger role in the regions.

Since 1990, major drives have been made to establish, within the countries, training schemes leading to qualification and certification of personnel on a national, regional and now on an international basis through the IIW.

South East Europe, Southern Africa, South East Asia, Western Africa and Australasia are examples of regions that have established training facilities and IIW ANBs which could play a very successful coordinating role in the establishment and delivery of various training schemes to meet the manpower requirements of the industry of the different regions. Ukraine could play an even greater role in its region.

Two important approaches could be the establishment of national or regional Educational Support Centres Networks and national or regional Technology Support Centres Networks throughout the world. Numerous outcomes could result giving tremendous benefits to the people and companies.

Conclusions and recommendations. The IIW is probably now in its strongest position in its history with an excellent team effort during the past eight years, culminating in a well balanced organisation with sound and enthusiastic leadership from its Board of Directors, excellent teams of world experts comprising the working units, a competent hardworking Secretariat, a range of relevant outcomes including products and services of value to its members, with increasing interest by more countries in becoming members. It has strong regional members which, with the support of IIW, industry, governments and aid agencies can deliver immense benefits to the regions throughout the world, as well as the region of Ukrainian influence.

IIW's colleagues in all countries can contribute to these objectives, in the following ways, amongst others:

• actively contribute to the IIW project «Improving the Global Quality of Life Through the Optimum Use of Welding Technology»;

• actively support the IIW initiative to improve the image of welding;

• nominate more delegates to participate in meetings of the IIW technical commissions and working units, which would be to the benefit of the individual, their companies and thus the country as a whole, as well as contributing to global welding technology development;

• consider linking into and expanding the IIW technology diffusion projects including the establishment of country and regional Technology Support Centres Networks;

• consider establishing country and regional Educational Support Centres Networks;

• contribute to the continual development, promotion and use of the IIW White Paper — WhiP «Improving Quality of Life Through Optimum Use and Innovation of Welding and Joining Technologies».

IIW looks forward to welcoming participants to future Annual Assemblies and to working with all people interested in improving the quality of life in the world.

We believe that, with the three attributes of Enthusiasm, Persistence and Cooperation, we can all work together in an excellent team effort to improve the quality of life of people globally.

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TRENDS IN JOINING TECHNOLOGY

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The main aspects which define the manufacture of technical products are reviewed. The characteristics to modern technologies of material joining are given concentrating on up-to-date developments. The forecast for the prospects of development of joint technologies including microjoints was made from the point of view of technical and cost efficiency.

Keywords: *technical products, materials, types of joint, mechanisation and automation, simulation, repair capability, arc welding, laser and EBW, hybrid processes, brazing, mechanical joints, microjoint, cost efficiency, progress trend*

General trends in the manufacture of technical products. As an introduction six trends are mentioned: namely multi-material-design of products, material developments, automation, simulation, repair and recycling of products. Reflecting these trends, the following observations could be made:

1. Modern technical products such as investment goods (e.g. building structures, transport vehicles of all kinds, installations and machines) or goods for daily use (e.g. household appliances, furniture and electronic devices) are increasingly being designed and manufactured in a form appropriate for different purposes. Within a product, this also means that the materials to be utilised must be chosen according to the multi-material design in a way which is suitable for the stresses and is cost-favourable.

As a result of this, the corresponding development of materials means that various materials are today used not only in one product but also even within one component or one sub-assembly — solid or in combination as composite materials. However, this is only possible if these materials can be connected and joined with each other in such a way that all the requirements necessary in the joints (strength, toughness, corrosion resistance etc.) are fulfilled there. For example, in automobile construction the such materials as steel, aluminium, magnesium and plastic are used and bodies-in-white for modern automotives have the following joining features techniques: structural adhesive-bonded seam — 90 m; punched rivets — 1.400; clinched spots — 280; blind rivets — 190; resistance-welded spots — 100.

In other bodies-in-white a variety of joining techniques are used, covering resistance spot welding, MIG/MAG welding, laser welding and laser soldering. More and more tailored blanks are used — combining sheets with different materials, thickness and surface treatment.

2. Today, the materials used for the manufacture of technical products are metals (particularly ferrous materials as well as alloys consisting of aluminium, magnesium and titanium for lightweight metal construction, nickel alloys for high-temperature-resistant or corrosion-resistant components, copper and its alloys for electrical components and for heat exchangers etc.), natural materials and plastics. The refinement of steels alone has led to the doubling of the steel qualities in the last 15 years. The development in the field of higher- and highest-strength steels alone is notable, these steels use transformation induced plasticity (TRIP) and twinning induced plasticity (TWIP) as micro structural effects (Figure 1). In plant and power station engineering, there are ever more stringent requirements on the materials with regard to higher temperature and corrosion resistances as well as to strength. For these materials, it is necessary to develop suitable welding processes and filler materials and to prove the long-time load capacity by long time tests.

There are similar developments in the case of the plastics. The composite materials and the material compounds have undergone an independent development. The combination of textile fibres with concrete or of fibres or nanoparticles with plastics (amongst other materials) indicate totally new paths in the development of materials and in their application. The integration of such materials into components necessitates totally new joining technologies if their advantages are not to be lost once again due to the joining.

3. One essential aspect with regard to the processing of materials by means of joining is the increasing requirement to mechanise or, even better, automate the joining operation in order to minimise the manufacturing costs. This applies not only to traditional joining and welding processes (arc welding, soldering and brazing and adhesive bonding) but also to newly

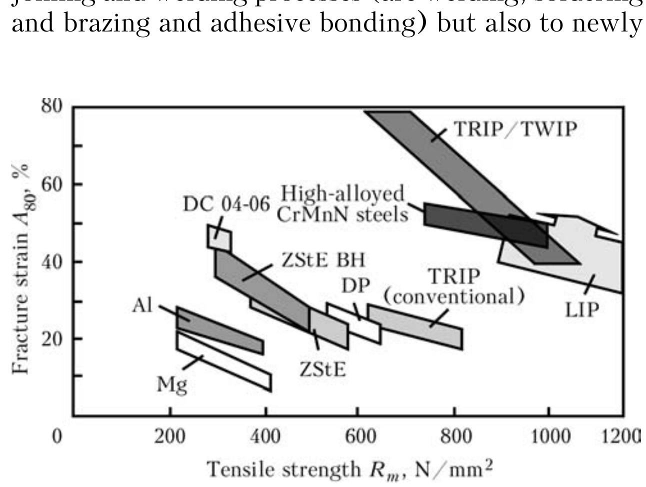

Figure 1. Development of high-strength steels

developed processes (hybrid processes, friction stir welding, and laser and electron beam welding).

With increasing wage costs, a lack of qualified welders at the same time and falling prices for robots, robots are being utilised increasingly, particularly in the industrialised countries. This development will continue in this way and, with better process simulation possibilities, robots will soon be introduced into small-scale series and single-part production as well.

4. For a few years, the simulation of the stresses on and manufacture of components has possessed ever more possibilities and significance because of the increasing computer capacity and the better software but, above all, because of the material parameters which are available to a greater extent.

5. A poor relation not only in today's development of materials and associated joining processes but also in the design of components is still the consideration of repair possibilities at an early stage if a component happens to be defective when it is manufactured, to be used improperly or for longer than originally intended or to be damaged because of a flawed design. For reasons relating to costs and environmental protection, such parts should not always have to be scrapped straight away. With suitable joining technologies, it is often possible to make such parts reusable.

6. Even if it is increasingly the case today that it is often more cost-favourable to replace a defective or damaged component than to repair it, it must be stated that this contradicts all the strategies of the conservation of resources. Here, rethinking will already begin in the near future — and questions relating to the repair possibility will thus come into play once again.

Joining technologies — recent developments. *Arc welding*. In addition to gas fusion welding, metal-arc welding is one of the oldest welding processes. At the beginning of the 20th century, manual electrode welding was utilised first of all. Even today, this process is still the most universally usable welding process. Filler materials are available for almost all the weldable metallic materials and can be developed relatively quickly even for new materials. Moreover, the process is largely independent of the welding position and of the environmental conditions. Therefore, it continues to be indispensable for assembly and repair tasks. Disadvantages relate to the difficult mechanisability of the process in comparison with other arc welding processes and to the environmental burdens originating from the process due to dusts which arise during the welding and may also be harmful to health. Therefore, it is necessary to take particular measures in order to protect the welders' health depending on the materials to be welded. In series and mass production, the process is increasingly being superseded by more efficient and more environmentally friendly processes.

It can be stated that the quantities of consumed filler materials all over the world are still valid indicators for the intensity welding techniques are used (Figures 2 and 3). In recent years, the proportion for manual electrode welding has dropped constantly, above all in the industrialised countries. But it should be stated also that more and more techniques are used, in which little or no filler materials are used.

Other widespread metal-arc welding processes are gas-shielded metal-arc welding, submerged-arc welding, tungsten-inert gas welding and plasma welding.

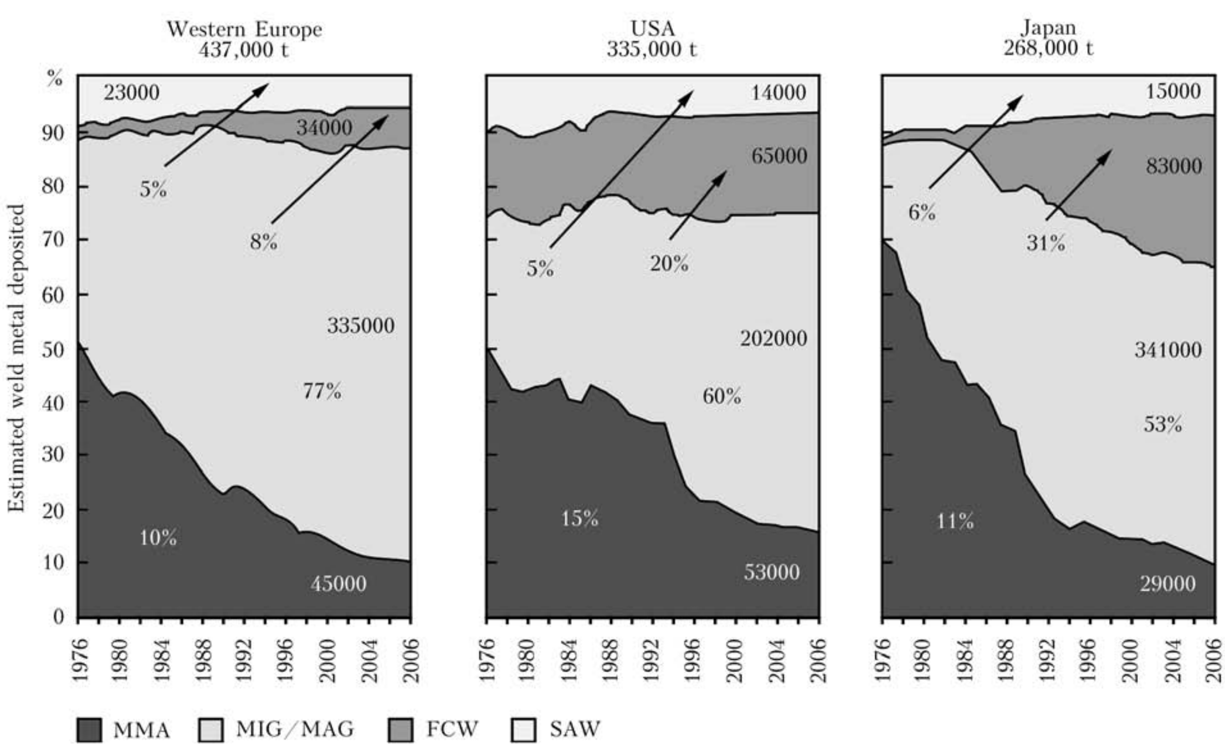

Figure 2. Reduced consumption of stick electrodes in industry countries

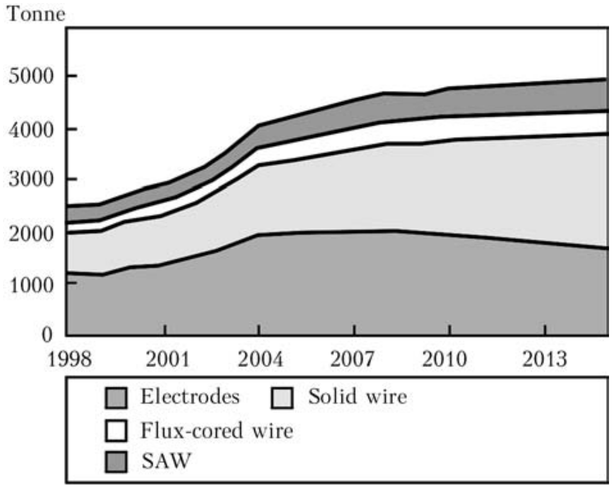

Figure 3. Worldwide consumption of filler materials by welding

Gas-shielded metal-arc welding is utilised as a semi-mechanised, fully mechanised or automatic process. Due to the modulation of the electric current, the process can be adapted to the respective special requirements caused by the material to be processed, the welding position and the component. Developments with regard to the controlled energy input as a cold arc or as cold metal transfer (CMT) have attracted attention in recent times. The processes control the metal transfer of short arc welding processes by reducing the current during short circuit phase (Figure 4) or by pulling back the wire during of just after metal transfer (Figure 5). These developments permit not only very low-spatter welding but also the welding of materials which only withstand a low heat supply respective low energy supply such as highest-strength or surface-coated steels. Both processes are also suitable for metal-arc brazing in a particular way.

The developments of the other arc welding processes should not be dealt with in any greater detail here. Anyhow, developments are to be expected in the future. The shielding gases for gas-shielded arc welding are being refined constantly with the objective of reducing the spattering, the costs and the environmental burdens.

Laser and electron beam welding. In the past ten years, the beam processes have undergone an enormous development and have been introduced into many fields of fabrication. Both processes are particularly suitable for fully mechanised or automated utilisation.

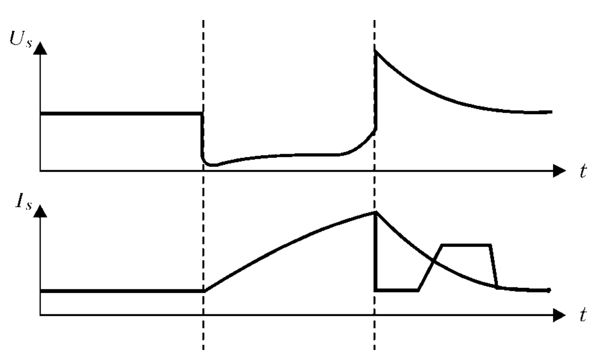

Figure 4. Principle of EWM cold arc technology

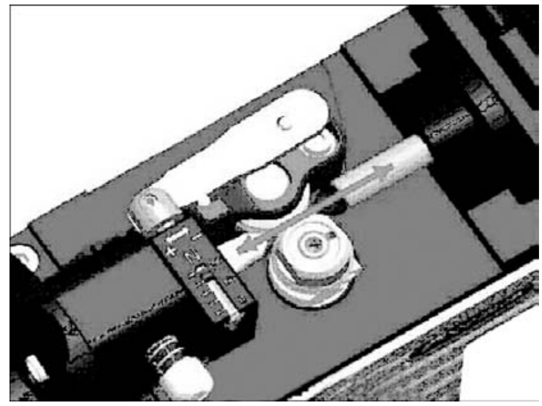

Figure 5. Principle of «Fronius» CMP process

Electron beam welding as the older of the two has been applied increasingly, above all due to the improved appliance technology, and was able to bring its advantages to bear. These are an extremely high power density and thus a low heat input even in the case of the thickest welds up to 250 mm and above. Large available vacuum chambers up to 630 m^3 permit the welding even of large-volume machine components (Figure 6). The possibility of splitting the beam allows the execution of several welds on one component at the same time. It should be noted that also non-vacuum electron beam processes are available, which show more and more applications in industry.

Laser beam welding has the great advantage that is can be used outside the vacuum but only in the material thickness range under 20 mm in general. This makes the process particularly suitable for the manufacture of tailored blanks made of different steel qualities and material thicknesses. Another advantage is, as in the case of electron beam welding, the low heat input as a result of the high energy density. With the remote technique, it is possible to use the effect of the laser beam even over a greater distance between the beam source and the welding position (up to 500 mm). This will be used increasingly in automobile fabrication in future (Figure 7).

Laser beam welding is also utilised in the processing of plastics. In this respect, corresponding requirements with regard to the light absorption must be set on the plastics to be processed.

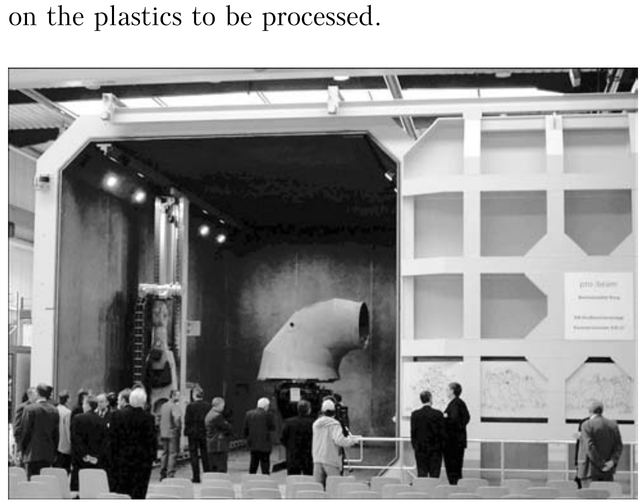

Figure 6. Very large vacuum chamber for electron beam welding

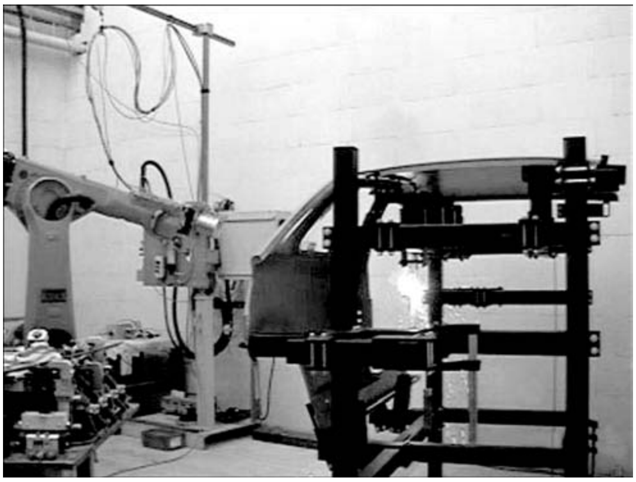

Figure 7. Remote laser welding

Friction and resistance welding. In recent years, there has also been a series of new developments relating to the friction and resistance welding processes.

In the case of friction welding, new developments in machine technology have led to the use of lateral relative movement of the parts to be welded so that it can be utilised for joining large sections which are not rotationally symmetrical. One special variant of friction welding is friction stir welding (FSW) which, however, is used exclusively for aluminium and its alloys in practice at the moment. The problem relating to its application to other materials (in particular, steel) is the low stability of the rotating tools (Figure 8). Developments are being made all over the world, covering different materials, thicknesses and dimensions (Table).

The major advantage of these processes is that the welding is carried out below the melting temperature and that this merely leads to a slight metallurgical change in the base materials to be joined. The great forces to be input into the workpieces are disadvantageous and necessitate very sturdy clamping jigs. Friction stir welding is utilised not only in rail vehicle construction and the aerospace industry but also for the leak-tight welding of covers into hydraulic control parts.

Figure 8. Friction stir welding of steel tubes

Friction stir welding of different materials

Material	Sample thickness, mm						
	Up to 1	1–4	4–8	8–12	Up to 25	Up to 50	Up to 75
Al — pure		D	D				
Al — 2xxx series		P	P	P	R	R	
Al — 5xxx series	R	P	P	P	P	R	R
Al — 6xxx series	R	P	P	P	P	R	R
Al — 7xxx series		P	P	P	R	R	
Al — castings		R	R	R	R		
Mg — AM series		R	R	D			
Mg — AZ series		R	R	D			
Cu — pure	D	D	R	R	D	R	
Cu — brasses		D	D	D			
Ti — pure		D	R	D			
Ti — α–β alloys		R	R	D			
Ni — pure		R	R				
Steels — mild		D	D				
Steels C–Mn		R	R	R	D		
Steels — stainless		R	R	R			
Pb — pure		D	D				
Zn — pure	D	D					

Notes. P — area of current FSW production use; R — area of current FSW research; D — area where FSW has been demonstrated.

No sudden refinements have occurred in the case of resistance welding. The refinement of the machine, control and computer technology has made the different process variants (flash butt welding, stud welding, etc.) even more reliable.

Hybrid welding processes. There has already been fundamental progress with regard to the development of combinations of various welding processes; further innovations are to be expected.

The combination of metal-arc welding with laser beam welding has been introduced into practice at a particularly quick speed (shipbuilding and automobile construction).

The combination of both processes (Figure 9) leads to the ideal exploitation of the respective advantages of both processes — the high energy density and low thermal load, the deep penetration, the high welding speed at high tensile strength of metal due to the laser, as well as the good gap-bridging capacity, the low lack of fusion, the addition of filler metal and metal microstructure modification due to the such low-cost energy source as arc. In the combination of both processes, it is possible to weld greater wall thicknesses in one layer than with each process on its own. This may give rise to considerable rationalisation.

In recent years, increasing significance has been attached to related joining processes. This may be attributed, in particular, to the multi-material design and to the increasing sensitivity of the materials to the heat input during the welding.

Soldering and brazing. Soldering and brazing relate to the joining of metallic materials below the solidus temperature with filler material. In the electrical and electronic sectors as well as in the skilled plumbing trade, soldering is used for joining electronic components, electrical cables and conductors, pipes made of copper and zinc sheets or galvanised sheets. Soldering is utilised in the jewellery industry too. The soldering temperature should be as low as possible so that solders with a low melting point (below 350 °C) can be used. Because of the toxic effect of lead, solders containing lead are no longer utilised anywhere in the world as a rule. Although substitute solders with similar properties and without any toxic side effects are available, they are not yet satisfactory for all applications. Thus, the developments are continuing.

Higher-strength joints between metals and ceramics are manufactured by means of brazing and high-temperature brazing. In this case, brazing filler materials made of totally different metals and metal alloys are utilised depending on the application and on the materials to be brazed. In addition to flame brazing with an oxy-fuel gas flame, arc brazing using the «cold» arc technologies mentioned above has become more widespread in recent times and is used in the automobile industry for joining galvanised sheets in bodymaking. It is conceivable that arc brazing will be utilised in other sectors.

Adhesive bonding. Adhesive bonding has been used increasingly as a «cold» joining method for processing both plastics and metals. Adhesive bonding has major advantages particularly for joining heat-sensitive materials. With the development of corresponding adhesives, it is today possible to manufacture joints between very different materials which even withstand stresses over a long time and across relatively wide temperature ranges. However, lower or higher utilisation temperatures (e.g. below −50 °C or above +180 °C) are still problematical. One universally known utilisation field is for the adhesive bonding of windows into cars, but more and more structural bonding takes place.

Mechanical joining. Another «cold» joining process is the mechanical joining or forming joining of materials, particularly of metals, which is known, for example, as clinching or toxing or punch riveting. Applications relate to joining sheets if the joint is exposed to low or, preferably, static stresses. In this case, surface coatings remain largely undamaged and corrosion protection is retained. Applications are for the manufacture of white-metal goods (i.e. kitchen appliances) and similar products and in the automobile industry and ventilation technology.

Hybrid joining processes. As already in the case of the welding processes, combinations of the related joining techniques with each other and with welding processes are also possible and are being applied and developed too. Today, the combination of resistance spot welding with adhesive bonding is widespread in the automobile industry. This combination combines high reliability with improved bodywork stiffness, improved corrosion protection and good economic viability because of the high cycle frequency in the fabrication. Today, such joints can also be repaired.

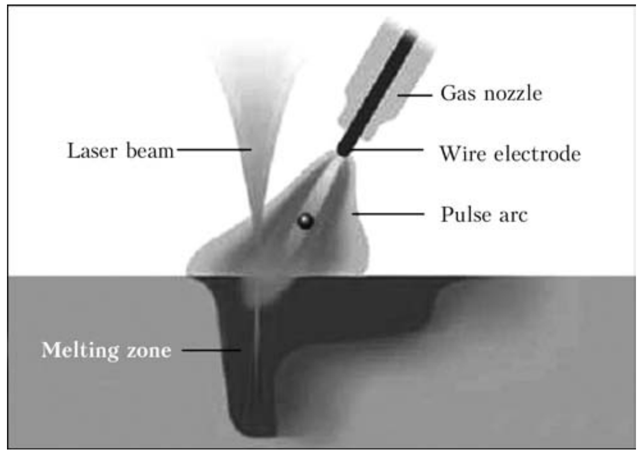

Figure 9. Laser-arc hybrid welding (high process stability, higher welding speed, good wetting of edges being welded, large weld volume, good metallurgy properties)

A combination of adhesive bonding with the mechanical joining processes leads to a considerable improvement in the crash strength of the joints in comparison with mechanical joining alone. In recent times, the joining of steel with aluminium has been a significant subject in the wake of the increased utilisation of aluminium alloys in motor vehicle construction with the objective of weight reduction. Not only screwing but also mechanical joining and adhesive bonding constitute suitable solutions. It is particularly interesting and promising to manufacture the joint between the two materials using a combination of welding (on the aluminium side) and brazing (on the steel side). With modern appliance technology, this can be done reliably using the electric arc.

Micro joining technology. Even if micro joining technology is hardly visible, it has become a permanent fixture in everyday life. The many helpers in the household, entertainment technology, communications technology and automobile technology are all no longer conceivable without electronics, sensors and actuators. It is not possible to foresee an end to the development and the proportion of electronics in our surroundings will grow further. The electronic systems are becoming ever more complex and smaller and the functional contents are rising almost into the immeasurable. The best example of this development is the mobile phone. While these were still really bulky devices with an aerial sticking out a long way a few years ago, they are today small marvels with which we can listen to music, watch videos, record pictures and films and, incidentally, even telephone as well. These developments became possible, amongst other reasons, due to the continuous refinement of micro joining technology. Following the trend towards the miniaturisation of semiconductors and passive components, joining technology had to adapt to ever smaller joints. This trend is undiminished especially in the case of the assembly and joining technologies such as: soldering; adhesive bonding (mechanical and conductive adhesive bonding), casting and packaging; strategies for diagnosis and testing and for proving reliability; modelling and simulation of the process and the component behaviour; mechanical joining; bonding (wire and wafer bonding); welding (resistance and laser).

The future in electronics, sensors and actuators is being driven by miniaturisation, progressive functional integration, higher thermal and mechanical loads as well as increasingly stringent requirements on reliability and cost reduction. In order to satisfy these requirements, it is necessary to fully exploit existing technologies right up to the physical limits and to develop new technologies.

Economic significance of joining technology. In the process chain for the manufacture of products, ever more significance is being attached to joining technology from an economic viewpoint too. This significance can best be portrayed by the proportion of joining and welding technology in the total value added by the fabrication of products. There are two general effects to be distinguished: first the production of goods for joining technology and secondly the application of joining technology in different branches.

The first effect: production of joined goods and services for joining (equipment, filler materials, auxiliary materials, health and safety as well as training and education) influence the whole line of added value and the German political economy. The total added value by this effects amounts to 2.24 bln euro generated by 37,654 employees. The second effect: application of joining technologies is instrumental in generating added value in a lot of branches. The total added value by this effects amounts to 24.76 bln euro generated by 602,386 employees.

The overall total added value of 27 bln euro of joining (manufacturing of goods for joining and application of joining technology) corresponds about 4.8 % of total added value of all producing trades and 640,000 employees (including civil building) in Germany.

Unfortunately, it is still very difficult to obtain corresponding statistical figures. For Germany, DVS (German Welding Society) has been presenting corresponding figures for some years. At the moment, efforts are being made to establish corresponding figures for Europe. In IIW (International Institute of Welding), there are attempts to establish such values for the whole world. Rough estimations indicate a global market of 40 bln euro for products related to welding.

Trends in joining technology — statements.

1. During the development of new technical products and the further development of existing technical products, greater attention is being paid to optimised material utilisation which also takes account of local stresses. Even individual components are being composed from different materials to an increasing extent. Examples are tailored blanks made of different steel sheets with various thicknesses and surface qualities or components which are coated locally against corrosion or wear. Furthermore, combinations of steel with light metals or plastics are being used ever more frequently in lightweight construction and the significance of nickel-base alloys is continuing to grow in the construction of power stations and aircraft engines.

2. To an increasing extent, joining technology processes will be necessary for this purpose and, in the future, will be core elements for quick, problem-free and reliable production — in this respect, they will be integrated into the chain of the manufacturing processes. Thus, joining technology remains economically significant; it is making a fundamental contribution to the value added by the producing sector and has good prospects of growth. Joining technology will play an exceptionally important role in all the phases of a product life — these phases encompass the design, development, fabrication, utilisation, maintenance and repair of a product as well as its recycling and disposal. In this case, consistently interdisciplinary approaches in research, development, fabrication and application will be adopted in order to incorporate requirements resulting from the product, production and material development.

3. Not only mechanisation and automation but also the use of industrial robots for joining will increase. For economic reasons, the simulation of processes and properties is becoming the key factor also for the application and further development of joining processes and materials. Those processes and materials which evade reliable simulation will no longer be used in the future. Simulated joining processes permit the virtual testing and optimisation of the joining processes even in advance of the production, permit the planning and implementation of quality-assurance concepts before the joining process and help during commissioning, operation and repair. At an early stage, they also provide information for the necessary training of personnel for the fabrication, maintenance and repair. The objective must be to permit a universal concept for the simulation of the entire process chain on the basis of the elements consisting of process simulation, structural simulation and material simulation.

4. Basically, it may be assumed that the definition of weldability until now (as a component property with the concepts of the welding possibility of the fabrication, the suitability of the material and the welding reliability of the design) must be refined by a definition of the joinability — with the subdivisions of the joining possibility, the joining suitability and the joining reliability. This terminology takes into consideration the fact that, in addition to welding technology processes, other joining technology processes such as brazing, adhesive bonding, mechanical joining and also coating are being used to an increasing degree.

5. Greater importance has been attached to repair and maintenance concepts especially for joined products in road-vehicle construction. Repair concepts must be an integrated part of the product development and must take account of the increasing utilisation of high-strength steels, light-metal alloys, plastics and tailored blanks as well as of the applications of the laser welding processes, adhesive bonding and mechanical joining. This is important because the joining processes applied in the production may have a direct influence on the possible repair costs of vehicles. Moreover, the costs of third-party and own-vehicle insurance are dependent not only on the accident frequencies but also on the repair costs. Joining processes which lead to rapid fabrication but generate high costs in the cases of repair may therefore be counterproductive. Modular construction methods which are suitable for repair are being applied especially in the case of vehicle construction. Concepts for qualified training in new repair techniques have been developed.

6. The people's justified wish for the protection of their environment is leading to particular expectations with regard to technology — this applies to joining technology as well. As examples, the requirements resulting from this can be described with the following headwords: economical handling of primary and secondary energy, conservation of raw materials, avoidance or elimination or storage of residual materials, selection and utilisation of reusable materials as well as recycling processes for joined components. In addition, measures for health and safety in joining technology remain urgent.

7. For the future, a competition between the joining processes is emerging in the applications. Here, the thermal joining processes are competing not only with each other but also with low-heat and «cold» joining processes. It is possible, in simplified terms, to make the following trend statements about individual joining processes:

• gas-shielded arc welding retains a dominant position and the latest research supports the applications and further developments of these processes. However, an estimation for the future suggests that gas-shielded arc welding will not grow as quickly as in the past years;

• the processes of resistance welding will hold a dominant position due to their process performance and productivity — anyhow they will lose applications, in particular because of the increased application of mechanical joining technology but also because of adhesive bonding. It remains to be seen, whether developments like hybrid processes (e.g. a combination of resistance spot welding and adhesive bonding) will prove its success;

• the beam-welding processes (especially the laser beam welding processes) will become far more significant as a result of the rapid transfer of the findings from the research to the application. In this case, the growth of electron beam welding will possibly slow down.

The necessity of using hybrid welding processes to a greater degree in practice is also shown. This is reflected in the expectation of using these to a greater degree in practice. In this respect, it is primarily the combination of laser welding with gas-shielded metal-arc welding which is regarded as a hybrid process. However, combinations of laser welding with gas-shielded tungsten-arc welding and with plasma welding are also being used. Basically, those welding processes in which different welding processes are coupled via a common molten pool and a common process zone thus exists are designated as hybrid welding processes.

8. The increasing complexity of joining technology is necessitating competence management in the companies. Here, competence is defined as the joining-together and exploitation of relevant knowledge in materials engineering and in fabrication and joining technology for a quite specific purpose. In this respect, the competence of a company is more than the sum of the competence of the individuals. The objective must be to assess and implement the experience available in the company, the existing facilities and proven processes in a proper and cost-effective way over the entire product life cycle. While paying attention to these conditions, joining technology will continue to account for a large proportion of the value added in the producing sector with prospects of further growth. Joining technology will gain acceptance even in difficult economic conditions. The consistent further development of joining technology entails investment in appliances, processes and infrastructure — however, particularly in people and in their knowledge and abilities.

We appreciate Dr. Schmitz, Robert Bosch GmbH, Schwieberdingen, for his interesting contribution to this work.

ADVANCED WELDING TECHNOLOGIES IN RECENT INDUSTRIES IN JAPAN (REVIEW)

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In this paper, a trend of welding technologies in design and manufacture of steel structures, such as ships and bridges, is reviewed. Further, the recent advance in welding atomization and application of new welding processes, such as laser and friction stir welding, in the Japanese industries is presented.

Keywords: *welded structure, shipbuilding, bridge, laser welding, friction stir welding*

Welding technologies in shipbuilding. Figure 1 shows the «Idemitsu-maru», the world first very large crude oil carrier VLCC, 1966, and a recent construction of advanced VLCC in shipyard. For the «Idemitsu-maru», a newly developed one-side automatic welding process was first employed for 490 MPa tensile strength grade steel. Modern VLCCs are built in double hull structures. The bottom hull plates of the large size are made by butt welding of plates fillet-welded with longitudinal stiffeners, and thus the welded bottom plates are assembled with sub-assembled members to construct double bottom hull blocks. The double hull structure became essential for crude oil carriers to avoid oil spills caused by going aground and orders for new double hull ships as substitutes of conventional single hull carriers increased. However, the weight of a hull block resultantly increased, and due to the total weight limitation the block joints with complex shapes which have to be made in a dock also increased. The building of the complex structures resulted in the reduction of fabrication efficiency.

Gravity welding, the most simplified automatic arc welding method using shielded metal electrodes, was developed in Japan during the World War II. One welding operator can handle several gravity welding machines at one time so that the production efficiency could be significantly improved. Although this welding process has recently been replaced by the other automatic processes, it is still used in some shipbuilding yards mainly for sub-assembled members. CO_2 welding is most regularly used in shipbuilding. Many type automatic CO_2 welding machines installed on a simplified carriage are used.

Automatic welding is used for blocks in the parallel part in the hull [1, 2]. Automatic CO_2 fillet welding machines with multiple torches are frequently used for welding of hull plates and longitudinal stiffeners. For high speed butt welding of large hull plates, one-side submerged arc welding with multi-torches electrodes using copper backing plates is employed in many shipyards. Semi-automatic welding or robot welding is used for welding of transverse and longitudinal members in assembly fabrication processes. Robot welding systems are also used.

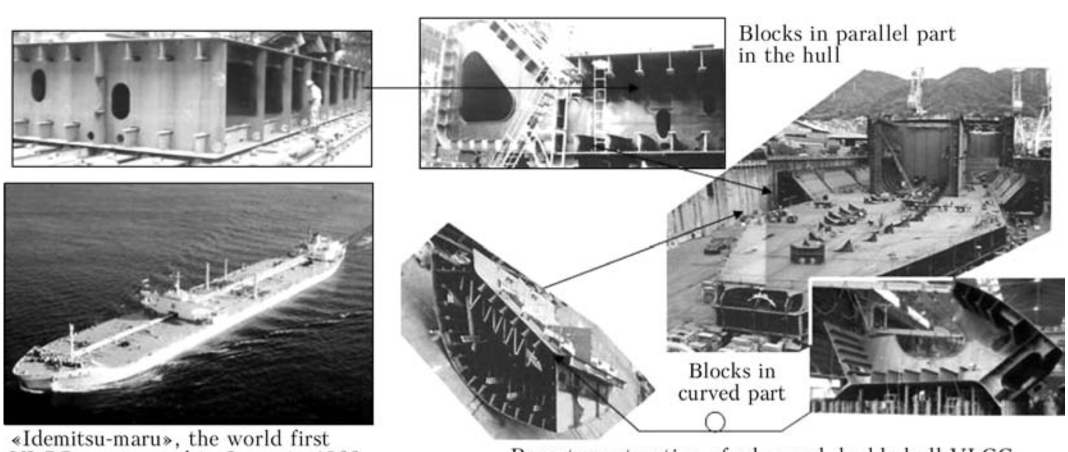

Figure 1. VLCC «Idemitsu-maru» and construction of advanced VLCC

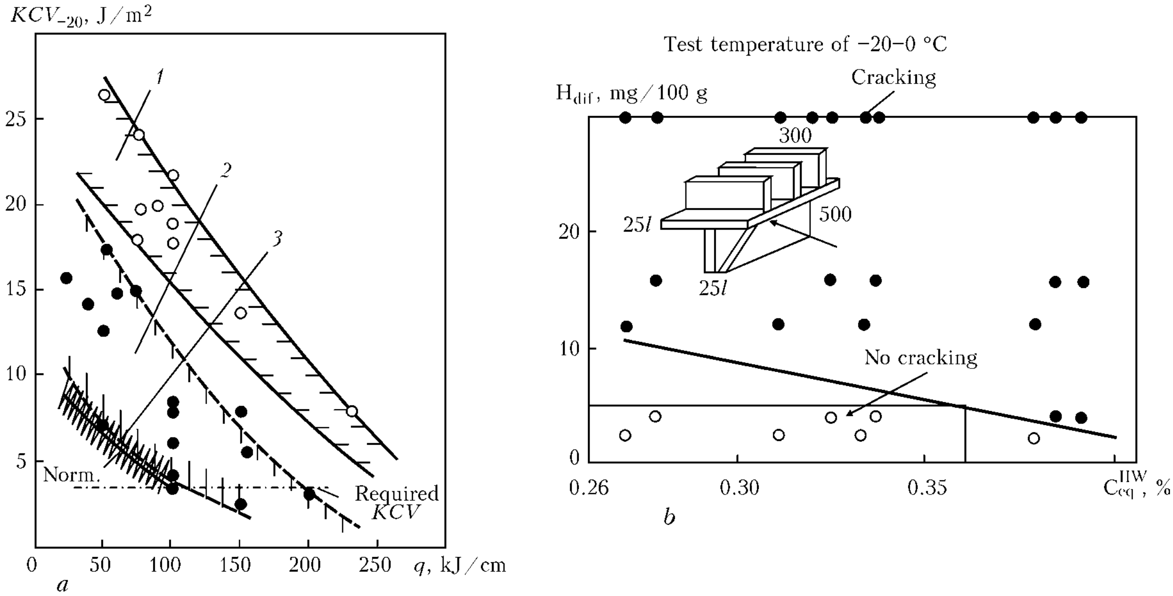

Figure 2. Effect of TMCP steel (E grade of NK rule) for high efficiency welding with large heat input (q) and prevention from cold cracking in fillet welding with no-preheat: *a* — notch toughness (Charpy impact test); *b* — cold crack test for overhead fillet welding; *1* — TMCP steel (large heat input resistant treatment); *2* — TMCP steel (non-large heat input resistant treatment); *3* — conventional (normalized) steel

After blocks are mounted, double bottom plates and side shell plates respectively are joined by block-to-block welding [3]. In block-to-block welding all sections of blocks are welded including longitudinal stiffeners. CO_2 semi-automatic welding machine and automatic welding machine on a simplified automatic carriage are mainly used, but submerged arc welding with flux asbestos backing is often used to block-to-block welding. In butt welding of side shell plates, automatic welding processes of electro-gas welding and CO_2 automatic welding are used. Simplified automatic welding robots of portable types are used for butt welding of longitudinal stiffeners.

The steel grade used for ships has changed from mild steel to high-strength steel. The yield strength has increased from 320 to 360 MPa, and 360 MPa to 400 MPa. In 1980s, the TMCP (thermo-mechanical control process) steel was developed and utilized to ship structures. The use of the TMCP steel facilitated the improvement of shipbuilding efficiency. The grain refining raises the strength and toughness of steel concurrently and thus, the addition of alloy element to a lesser extent keeps the steel strength resulting in the reduction of carbon equivalent. The TMCP steel most used in recent shipbuilding is of a type of controlled-rolled accelerated cooling [4, 5]. Figure 2 shows the effect of TMCP steel for high efficiency welding with large heat input method and prevention from cold cracking in fillet welding with no-preheat [6]. Figure 2, *a* shows relationships between the welding heat input and Charpy impact values of fusion line and HAZ in high heat input butt welding of steel plates for hull structures. The heat input in shipbuilding had been limited to 10 kJ/mm for the conventional steel including normalized steel. However, the use of the TMCP steel and high heat input resistant steel enabled us to employ ultra high heat input welding processes such as one-side submerged arc welding, electro-gas welding and electro-slag welding. Figures 2, *b* shows the effect of the steel carbon equivalent C_{eq} and diffusible hydrogen content of weld metal on cold cracking in overhead fillet welding. Preheating had been conducted for overhead fillet welding of the conventional steel to avoid cold cracking. The steel whose C_{eq} is not higher than 0.36 % without preheating became possible provided that low hydrogen type electrodes were used.

A marine accident of a containership happened in 1997 [7]. Figure 3 shows the structure of containership and a concept of a safety assurance of welded joint of hatch-side coamings against brittle fracture. Cargo containers are required to be stowed down to the bottom of the ship and thus, the very large openings on decks are prepared in containerships. In order to maintain the longitudinal strengths of containerships, hatch-side coamings vertically piercing up to the upper deck are fixed. Recently, very large containerships are built and those carrying more than one thousand containers are planed to be built. In these ships, the thicknesses of coaming plates of 390 MPa yield strength (YP390) grades attains to 80 mm. The employment of electro-gas welding with a large heat input is desired from a viewpoint of production efficiency. However, welding with a large heat input tends to degrade weld metal and HAZ toughness and the safety assurance against brittle failures becomes an important concern. The TMCP steel with high toughness exhibits the preferable resistance against brittle fracture initiation. However, according to the double integrity concept the suitable crack arrest capability is required so that a running crack can be arrested even though a brittle crack should be initiated and propagated.

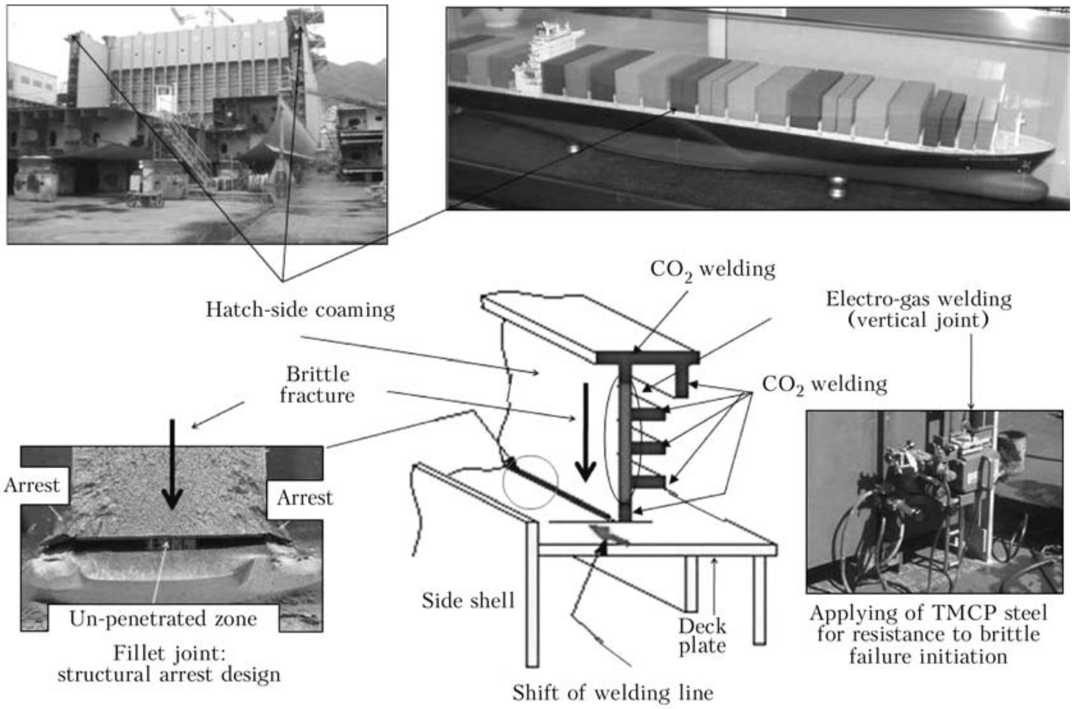

Figure 3. Structure of containership and concept of a safety assurance of welded joint of hatch-side coamings against brittle fracture in design

In the case of full penetration welding of a deck plate of a conventional grade and a hatch-side coaming, a running crack propagates in the weld and passes through the deck plate. To prevent this situation, deck plates with a ultra high arrest property are used in some shipyard. However, another shipyard consider that the use of fillet welds is safe enough instead of using of full penetration butt welds because the weld of a hatch-side coaming and deck plate transfers only shear stresses. The use of fillet welds results in arresting a crack in the welds and it is considered unnecessary to use steel with an ultra high arrest property for deck plates. This concept is called as the «structural arrest design». When partial penetration welds are used together with the employment of proper groove shapes, a crack propagates into the deck plate but eventually stops in the deck plate even when a conventional grade of steel is used for deck plates.

Welding technologies of bridges. The Chalkiness bridge in U.S. was built first by welding with high strength steel of a 780 MPa tensile strength grade (HT780) in 1958. This steel was developed originally for upper decks of an aircraft carrier «York Town» [8] and was called T1 steel. At the same age, Japan imported this steel and fabricated a spherical gas storage tank by the T1 steel. The welding technology of HT780 steel was transferred to the fabrication of bridges.

Since 1970, HT780 steel was begun to be used for bridges and a bridge made of a large amount of HT780 steel was the the Minato bridge in 1974. For the Seto bridge built in 1988, HT780 was partly used. The Akashi-kaikyo bridge, the longest suspension bridge in the world, was completed in 1998 with a large amount of HT780 steel first since 1974.

The Akashi-kaikyo bridge was fabricated by stiffening truss girders of 30 mm thickness. The necessary preheat temperature for HT780 steel was originally 100 °C. However, C_{eq} and the chemical composition susceptible to weld cracking P_{cm} of HT780 steel of Japan were year by year decreased and the necessary preheat temperature for HT780 steel was reduced to 50 °C in the Akashi-kaikyo Bridge with plate thickness of 30 mm. The reduction of a necessary preheat temperature is very beneficial in bridge fabrication because of minimizing distortion of members to be welded and consequently shortening fabrication time.

The Seto bridge is the only rail road bridge constructed with HT780 steel and a fatigue-resistant design was introduced after conducting a number of fatigue tests. The improvement of fatigue strengths of high strength steel, especially HT780, is still a challenge to be solved.

In bridge fabrication, multi-torches fillet welding machines and automatic fillet welding machines on simplified carriages are used as they are in shipbuilding. Recently, the rational design concept prevails in fabricating bridges. Figure 4 shows the structures of rational design concept bridge and field welding. In plate girder bridge of the new design concept shown in Figure 4, *a*, the number of main girders changed to three lanes per three main girders from two lanes per four main girders in conventional design bridge. The bridge by the rational design concept is called the minimized girder bridge. The box girder of a type of three lanes per two main girders shown in Figure 4, *b*, is 100 m in the span length. This rationalization in bridge designs was enhanced by the chorological change of relative labor and steel costs. Before 1980s, labor costs were relatively cheep compared with steel

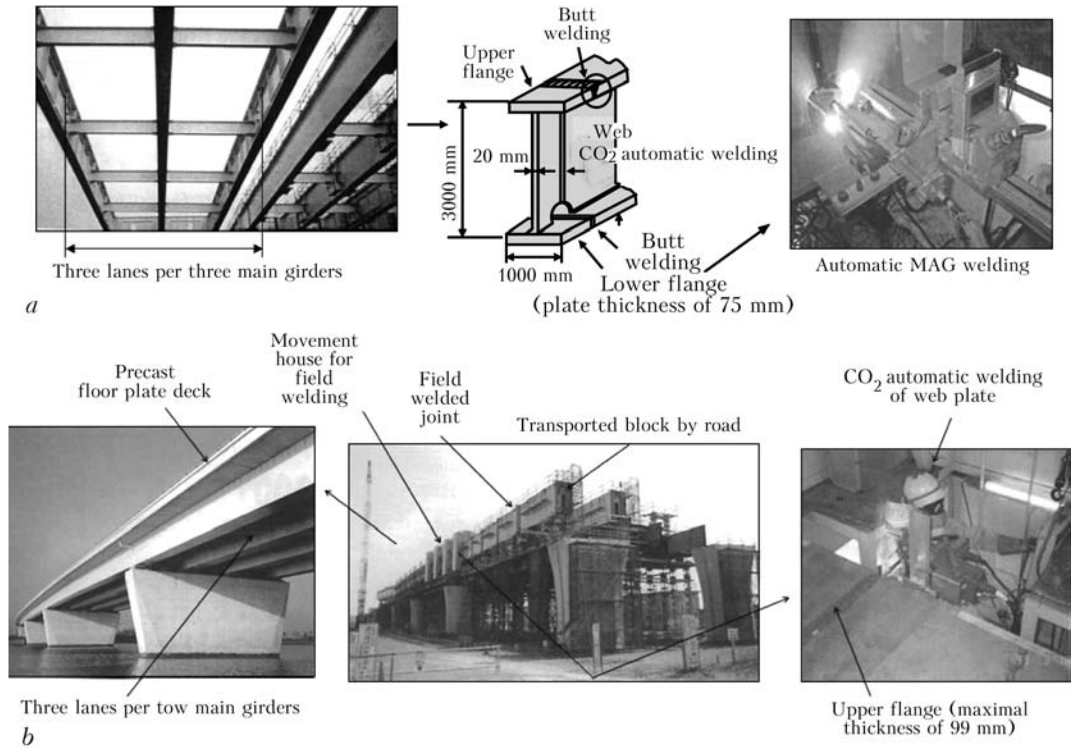

Figure 4. Structure of rational design concept bridge and field welding: *a* — plate girder bridge; *b* — box girder bridge

costs. Therefore, the complex design including welded joint was made in such that the width and thickness of flanges were deliberately designed at a minimum material use but at most effective tress transfer and supplemental members were welded to connect girders. This resulted in an increase in welding work. Recently, labor cost relatively increased and simple welded structures were designed so as to minimize welding work in spite of leading to a steel consumption increase. The flange thickness of the girder became as heavy as 100 mm and a friction grip connection method between stiffening girders by high tension bolts became impossible. Thus, welding was unavoidably employed, and Figure 4 also shows field welding of heavy bridge girders. For a TS590 grade steel plate of bridge, C_{eq} and P_{cm} reduced by TMCP steel, and became to weld without preheating even when it was as heavy as 100 mm.

The Irtysh river bridge in Kazakhstan was built by a Japanese constructor. The stiffening girder blocks were fabricated in Japan and they were transported by the Siberian railway. The girder blocks were assembled into large size blocks on site and the blocks were lifted and connected to hunger cables followed by being welded each other. The materials for the bridge were specified as the −50 °C use. TMCP steel was used and welding heat input was limited to a certain level.

In construction of the main tower of suspension bridge, site joining of tower blocks had been usually friction grip connected by high tension bolts. But joining by welding was first employed in the Hakucho bridge. The welding was used because of obtaining smooth beautiful tower surfaces. The accuracy of less than 1/5,000 (20 mm per 100 m) was required for the suspension bridge tower and thus, a special caution is necessary for welding distortion. A degree of welding shrinkage at the block joints differed by the welding conditions. It was necessary to uniformly compress the whole section of blocks to minimize bending of the tower. In another suspension bridge, the towers of about 100 m height were fabricated in a factory, transported to the construction site by sea and package-installed by floating crane.

In 2003, a new suspension bridge was constructed along the Chalkiness bridge in U.S. The girder blocks as heavy as 600 t were fabricated in Japan and they were transported in the North Pacific Ocean in winter. The blocks were directly lifted from ship and connected each other on site. In shop welding of steel floor plate decks, the quality requirements for welded joints of through ribs were so severe to avoid failures caused by fatigue.

Welding technologies of laser and friction stir welding. In Europe, laser welding is actively employed in shipbuilding and friction stir welding (FSW) is increasingly used to aluminum ships. In Japan, however, laser welding and FSW are employed to a much lesser extent than in Europe because Japanese shipyards build mainly ocean ships. But, both welding process have been increasingly employed in Japanese industries other than shipbuilding.

Figure 5 [9] shows the employment of FSW to the «shin-kan-sen» and laser welding to railway vehicles. FSW is aggressively used to fabricate railway vehicles in Japan. At the starting time of «shin-kan-sen» service, steel was used as a structural material for bodies and their structures were of a semi-monocoque type constructed by spot welding. Recently, aluminum alloy is used for bodies for reducing their weight to

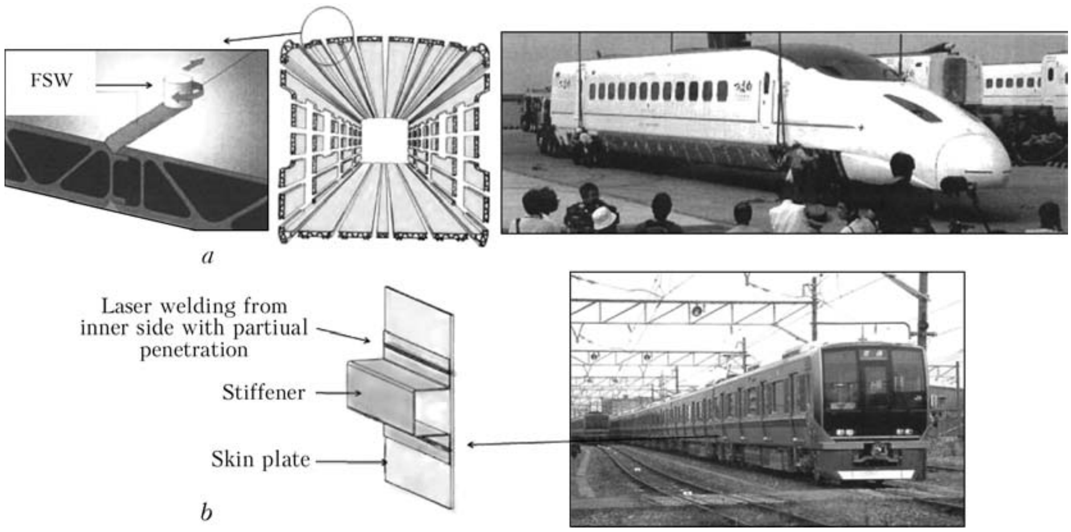

Figure 5. Employment of FSW to the «shin-kan-sen», Japanese bullet train, and laser welding to railway vehicles: *a* — FSW of double skin body extruded aluminum rods of Kyusyu «shin-kan-sen»; *b* — laser welding of 321 series stainless steel for alternating current electric commute train of West Japan Railway Company

enable a high speed service. The structure of the body changed from a steel semi-monocoque type to a type of double skin welded with extruded aluminum rods. This is an example that a change of welding processes induced a change of structures. Laser welding began to replace spot welding in fabrication of railway vehicles in order to increase the structural strength for the safety sake in traffic accidents [10]. Lately laser welding was also employed to the joint of double skin extruded aluminum alloy rods of railway vehicles.

The techno-super-liner, super high-speed ship, is the Japanese first and only ship welded by FSW. The employment of FSW was slower in Japan than in Europe since there were lesser demands for high-speed aluminum ships compared with Europe. A lot of stiffening panels made of extruded rods by FSW were used to upper decks of the super-liner [11].

Figure 6 show the employment of FSW for bridge member and a planed concept of laser welding of bridge member [12]. Figure 6, *a* shows a bridge with a pedestrian road added to the existing bridge. Although the existing bridge was reinforced, aluminum floor slab plates jointed with extruded rods by FSW were used to reduce the weight of the road of newly

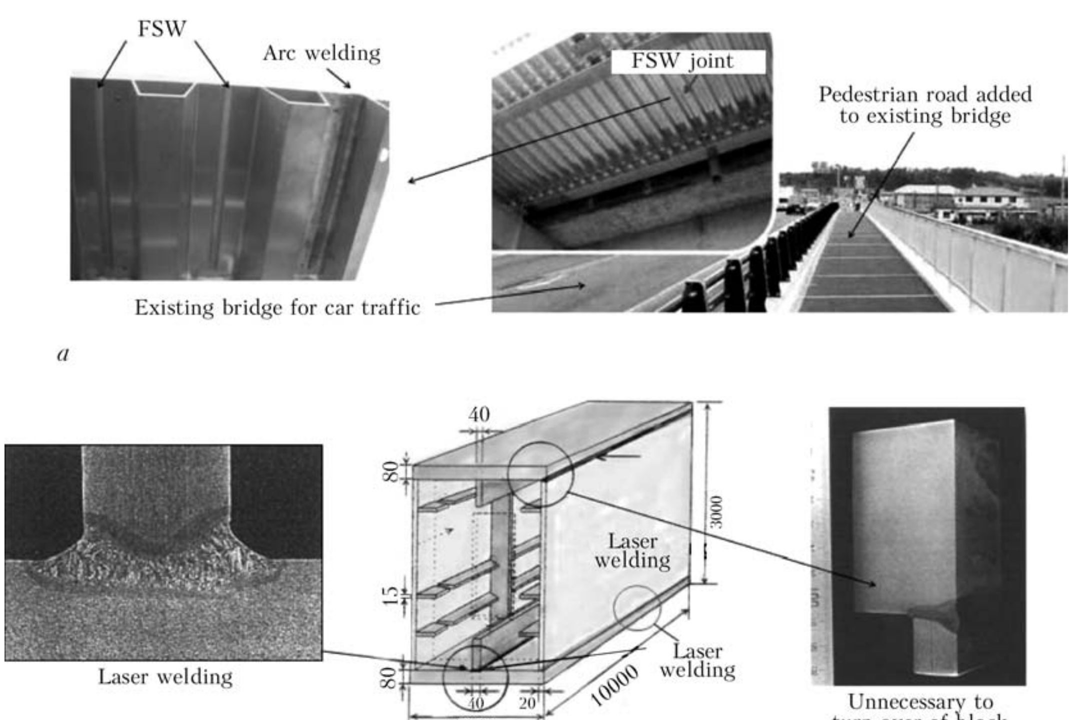

Figure 6. Employment of FSW for bridge member and a planed concept of laser welding of bridge member: *a* — FSW of bridge member; *b* — laser welding of bridge member

erected blocks. The direction of FSW was transverse to the bridge axial direction. The possible panel width welded by FSW was limited to 2 or 3 m and thus, several FSW welded panels were joined by arc welding to fabricate a block to be mounted. FSW welding was conducted not by fabricators but by aluminum makers. At present time, the employment of FSW to bridges is limited to pedestrian roads. Figure 6, *b* shows a planed concept of laser welding of a bridge box girder of the rational design concept. The use of laser welding makes it possible to fabricate big bridge blocks without the time consuming work of turn-over as required in arc welding. Further, laser welding of stiffening ribs is expected to increase their ultimate limit state strengths.

CONCLUSION

This review described the recent trends of welding technologies in the designs and fabrications of steel structures such, as ships and bridges, in Japan and it referred to the employment of new welding processes of laser welding and FSW to steel structure fabrications. It should be noted that steel with high qualities provided by Japanese steel manufactures has assisted fabricators to produce steel structures with improved performances and greatly contributed to the progress in manufacturing technologies in Japan. Although the review was limited to ships and bridges, the authors would hope this article helpful to the readers.

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MODERN NON-DESTRUCTIVE TESTING MEANS — MAIN TOOL FOR STRUCTURE CONDITION EVALUATION

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Diagnostics is an integral part of the technological process in manufacturing materials and products. Availability of high-quality materials and technologies of structure fabrication in the absence of effective diagnostic methods does not guarantee safe operation. Procedure and means of technical examination of various objects developed at ETC «Welding and Inspection» at the N.E. Bauman MSTU, are described.

K e y w o r d s : *non-destructive testing, welded structures, residual life, technical examination, flaw detection equipment, design procedure*

By US data the cost of testing operations in manufacturing of defense industry products reaches 25–35 % of the total product cost. In construction industry these costs are equal to 10–12 %. In Russia the cost of inspection and diagnostics is usually 15–20 times lower.

At present the importance of non-destructive methods of testing and diagnostics is particularly great, as depreciation of the processing equipment fleet in individual cases is higher than 65 %. In the near future, in order to prevent accidents, it is necessary to develop technologies and equipment for evaluation of the residual life of the most critical facilities in service. Solving this problem is given a lot of attention both abroad (Germany, Ukraine, China, etc.) and in Russia.

Table 1. Initial data required for determination of residual life of welded structures in the presence of defects

1. Data on the examined object
1.1. Type and overall dimensions of the welded structure
1.2. Composition of base and weld metal
1.3. Nature and purpose of working load
1.4. Operating conditions (environment, temperature)
1.5. Specified operating life
2. Data on the detected defects
2.1. Defect type (surface, internal, plane, bulk)
2.2. Location (base metal, weld, HAZ)
2.3. Dimensions and depth of location beneath the surface
2.4. Determination of the stress-strain state in the defect zone
3. Data on material properties in the defect zone
3.1. Initial mechanical properties and those measured by the instrument
3.2. Crack resistance criterion (K_{IC}, K_{th}) and limit ductility ($\varepsilon_{i\,lim}$)
3.3. Degree of deterioration (degradation) of material properties in operation

In Russia good results have been obtained, in particular, as regards design of highly-informative flaw detection equipment, and development of procedures for calculation of the residual life of individual facilities. Developed instruments and tools are based on the most recent achievements in the field of ultrasonic flaw detection, informatics, radioelectronics and are on the level of the best analogs in the world in terms of their performance.

This paper describes the procedure and means of technical examination of various facilities developed at ETC «Welding and Inspection» at the N.E. Bauman MSTU.

In order to calculate the residual life of a pipeline, it is necessary to have at least 34–37 parameters. The main of these parameters are given in Table 1.

It is seen that the data in sections 1 and 3 (except for item 3.3) can be obtained from designers and production people. Characteristics in sections 2 and 3.3 are obtained using equipment for NDT.

At evaluation of the technical condition of large-sized facilities (vessels, gas holders, tanks, etc.), as well as facilities with greatly ramified pipelines (compressor stations) conducting 100 % NDT appears to be a complex and costly operation (Figure 1). Acoustic emission (AE) diagnostics is applied at the first stage to examine this type of products.

Methodology of AE diagnostics developed at the N.E. Bauman MSTU, is based on application of new integrated AE energy parameters of spectral and regression signal (Figure 2), as well as individual wave components to identify the defect type, assess the degree of its development and the stage of structure pre-fracture from the propagating crack. AE diagnostics of plastic deformation mechanism of micro- and macrocracking, different types of corrosion and corrosion cracking is possible.

Vector-energy analysis and experimental studies of distribution of the energy flow density, AE power and their energy spectra for the longitudinal and transverse waves and total field around the crack showed the good prospects for application of AE flaw detection based on recording the individual wave components. Identity of the energy spectrum for the longitudinal and transverse waves and total AE field from a common disturbance source (deformation through slipping, crack propagation) was established for the studied objects. A linear dependence was found between the mechanical energy of deformation and acoustic energy of the total field, as well as of the longitudinal and transverse waves. It is shown that the energy distribution of the total AE field and of its individual components around the crack tip is similar to the configuration of plastic deformation zone. Application of probability regions of the indices of diagnosed processes (AE sources) plotted by statistical processing of AE signal flow parameters for identification of AE sources turned out to be effective.

Thus, when dispersion ellipses (average signal energy and median frequency) are used as informative indices, identification of plastic deformation and propagating microcrack by this procedure is performed with a high degree of validity. Error of microcrack classification against the background of plastic deformation was 3 %.

Scientific and methodological developments formed the basis of creation of 16-channel AE measuring system AEIS, which provides real-time localizing, identification and evaluation of the degree of criticality of the propagating defect.

The following procedure was accepted at evaluation of the technical condition of the main pipelines. After 100 % in-pipe diagnostics the most potentially dangerous areas of the pipeline are determined, except for the butt welded joints.

As in-pipe diagnostics does not provide an accurate instrumental evaluation of the dimensions of defects detected in the pipe body, and practically does not detect the defects in welds, the pipelines are subjected to further inspection. For this purpose, it is uncovered from the soil, and installed on special pedestals. Used for this purpose is a specialized automated ultrasonic unit «Avtokon-MGTU» developed at the N.E. Bauman MSTU.

Self-sufficient automated robotic system is a displacement mechanism carrying an 8-channel ultrasonic flaw detector with the controlling processor and acoustic system. The control panel has a screen for following the control process and system control buttons. Control results are saved by the processor (up to 300 m of the weld) with subsequent re-saving to the computer for further printing-out and establishment of a data base. The system is mounted on the controlled item, and moves along the welded butt automatically following it without any additional devices. The scanning mechanism is held on the pipe surface by permanent magnets built into the wheels. The unit is small-sized, and easy to operate and is serviced by two operators. Its comparative characteristics are given in Table 2.

At flaw detection of the pipe body «Avtokon-MGTU» unit (furtheron called scanner) is moving at the speed of 2 m/min along the longitudinal weld due to application of a high-accuracy seam tracking

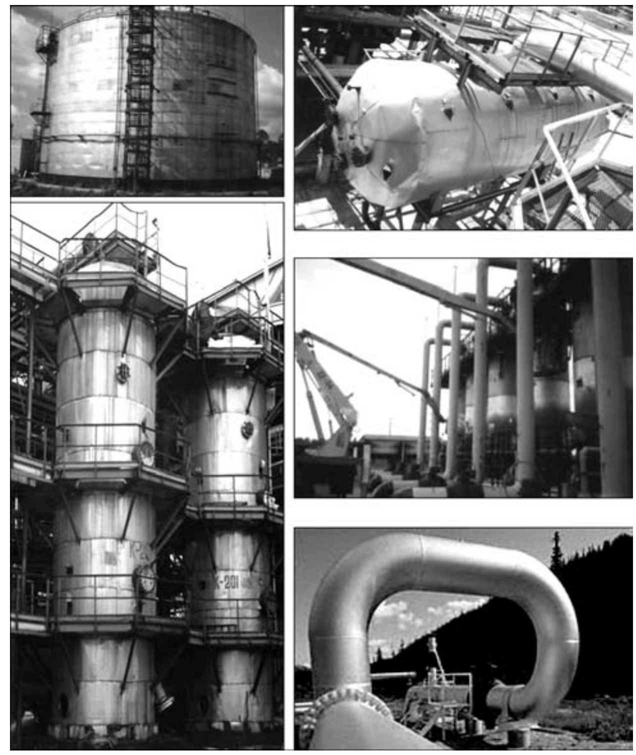


Figure 1. Examined objects

sensor (Figure 3). In the case of inaccessibility of the longitudinal weld, a flexible strip (tape measure) is fastened along the pipe generatrix, which is used as a guide for scanner displacement. Flaw detection results are saved in the computer memory and printed-out in the laboratory (Figure 4). At flaw detection of circumferential pipe butt joints the scanner is moving around the perimeter along the weld (Figure 5). Test operation of the scanner (more than 400 km of different typesizes of pipes of 1620–1420 mm diameter with the wall thickness of 8–20 mm have been tested) showed the high detectability (about 97 %) of practically all the types of discontinuities in the pipe body. The validity of defect detection in the circumferential butt joints of pipes was more than 85 %.

It should be noted that the currently available best foreign analog «Pipe WIZARD-PA», RTD Company,

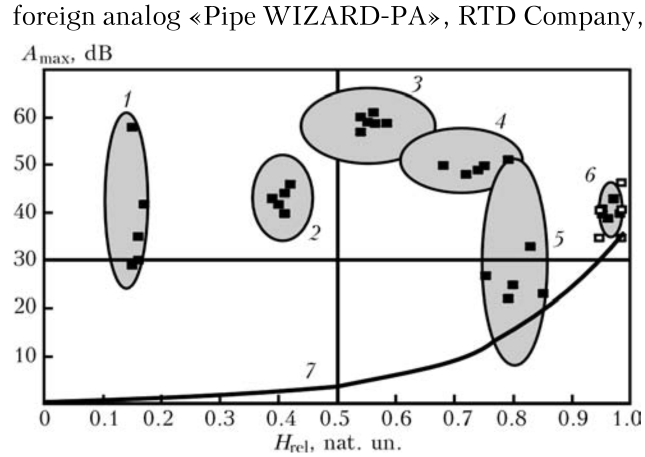


Figure 2. Results of AE testing of large-sized samples in the diagnostic diagram: *1* — unstable crack, lack-of-penetration; *2* — growing crack; *3* — propagating delamination; *4* — multiple bulk defects; *5* — plastic deformation, stable crack; *6* — corrosion cracking; *7* — defect level

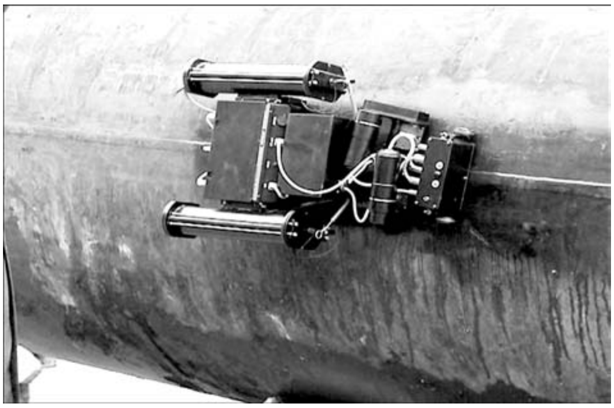


Figure 3. Flaw detection in pipe body by «Avtokon-MGTU» unit

can only test the circumferential butt joints (Figure 6), and requires the availability of a specialized vehicle with a diesel generator.

An essential drawback of contact scanners is the need to perform special labour-consuming surface preparation and feeding special fluid into the contact zone. To overcome this drawback ETC «Welding and Inspection» together with SPA INTROTEST developed and tried out on actual objects a contacless electromagnetic acoustic automated scanner (Figure 7). Testing demonstrated the high sensitivity (~ 0.1 T) to internal and external defects in the weld and the pipe body. It should be noted that the developed scanner has no analogs.

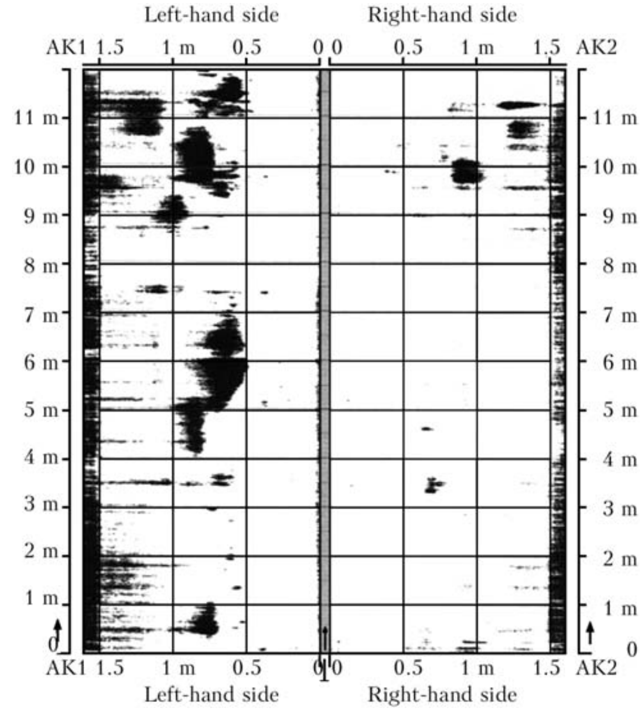
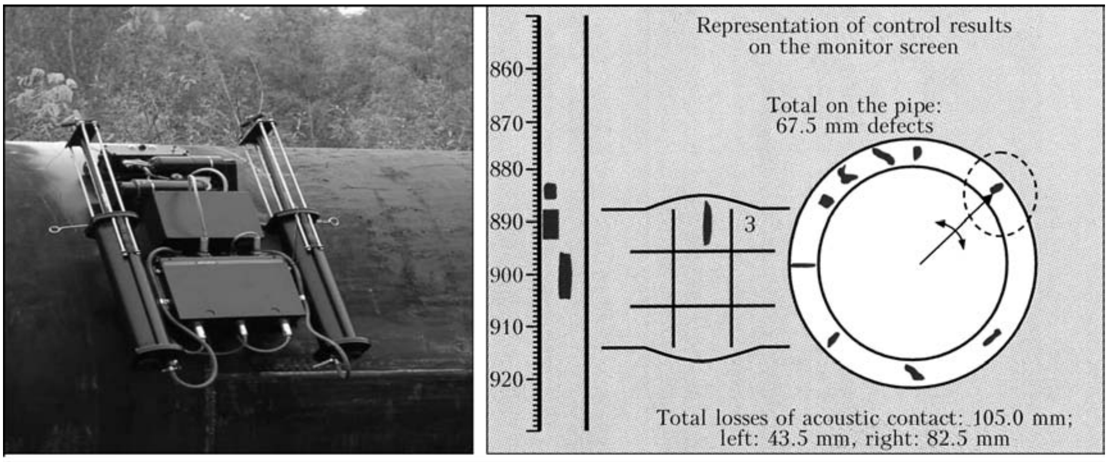


Figure 4. Ultrasonic diagram of pipe body

At evaluation of the quality of welded joints on difficult-to-control NPP items, «Avgur» type systems turned out to be the most effective. These systems use coherent methods of signal processing (Figure 8) de-

Table 2. Comparative characteristics of Pipe WIZARD-PA (RD TECHTM) and «Avtokon-MGTU» systems

Parameter or characteristic	Pipe «WIZARD-PA»	«Avtokon-MGTU» system	Note
System self-sufficiency	Within the length of communications cable of the mobile block and hose for couplant feeding	Complete	At pipeline control the main block of Pipe WIZARD-PA should be mounted on a car, and cable and hose length should be not less that 20 m
Scanning method	Automatic, along a guide mounted on the weld	Automatic, without additional devices	Avtokon-MGTU is fitted with a sensor for tracking weld reinforcement bead or flexible strip
Weight	More than 50 kg without the weight of the external computer, couplant tank, hoses and cables	Not more than 18 kg	Pipe WIZARD-PA is not portable
Range of controlled thicknesses of pipeline base metal	From 7 up to 32 mm	From 6 to 35 mm at acoustic module replacement	In most cases pipeline base metal thickness is not less than 8 mm and not more than 30 mm
Range of working temperatures	From −15 up to +30 °C	From −40 up to +50 °C	Testing most often has to be performed in winter, i.e. at below zero temperatures
Main control results	Defect detection, locating and measurement of conditional dimensions	Defect detection, locating and measurement of conditional dimensions	Same
Function of acoustic coupling monitoring	Yes, separate transducer by reflection from pipe inner surface	Yes, at each starting of each channel without additional devices	–
Control scope	Circumferential welds	Circumferential and longitudinal welds, pipe body	–



Butt number in welding log	Pipe wall diameter × thickness, mm	Welder's initials	Sensitivity around sample contour, dB	Description of found defects						Conclusion: fit, repair, cut out
				View	Type	Depth	Length	Height	Coord	
541	1420 × 16		21	E	P	v	17	3	635	
				A	P	v	10	2	1618	
				A	O	v	4	2	1680	
				AK	–	–	16	1932	–	

Figure 5. Flaw detection of circumferential pipe butts

veloped at SPA «Ekho+» under the guidance of Prof. A.Kh. Vopilkin.

Systems using coherent methods of defect visualization, have a principal advantage over the traditional flaw detection methods: they use much more information about the defect, thus allowing generation of images with a very high resolution — of the order of the used sound wave length — with a high signal-to-noise ratio, readily reproducible at repeated testing. These images depend to a much greater degree on the phase components of the measured acoustic field scattered by defects than on its amplitude.

In NPP with high-power boiling type reactors (RMBK) the greatest scope of control was performed on welded joints of Dn 300 pipelines. These pipelines are made of pipes from 08Kh18N10T steel with the rated values of outer diameter of 325 mm and wall thickness of 12–18 mm.

The most characteristic defects in these welds developing in operation are longitudinally and transversely oriented surface cracks forming by the mechanism of intercrystalline stress cracking. Testing was performed using «Avgur» series systems and a ring scanner (Figure 8, *a*).

Welded joints of Dn 1200 of WWER-1000 reactor are characterized by a large thickness (72 mm) and presence of a fillet from which cracks most often initiate in service.

Figure 9 clearly shows a diagonal transverse crack against the background of signals from the root and fillet. Proceeding from the obtained data, a test protocol was made, which contains the data on the defect dimensions, location and orientation. Results of subsequent uncovering confirmed the accuracy of the determined parameters.

At extension of operating life of NPP steam generators with WWER-440 reactor plants the problem of ensuring valid diagnostics of the composite welded joint of the transition ring and Dn 1100 nozzle of the steam generator becomes particularly urgent (Figure 10). The complexity of solving this problem arises from application of thick-walled austenitic materials and transfer electrodes. Moreover, design of this welded joint did not envisage the possibility of

Figure 6. Pipe WIZARD-PA scanner, RTD Company

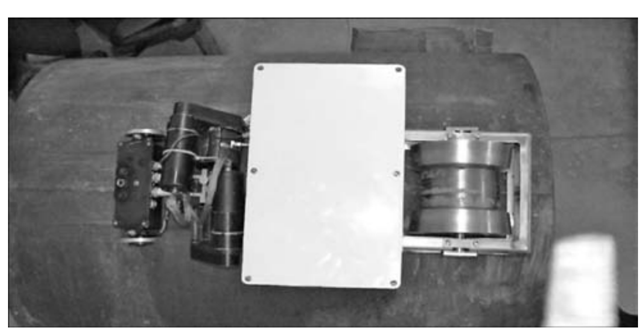


Figure 7. Electromagnetic acoustic flaw detector scanner for monitoring the gas pipe base metal

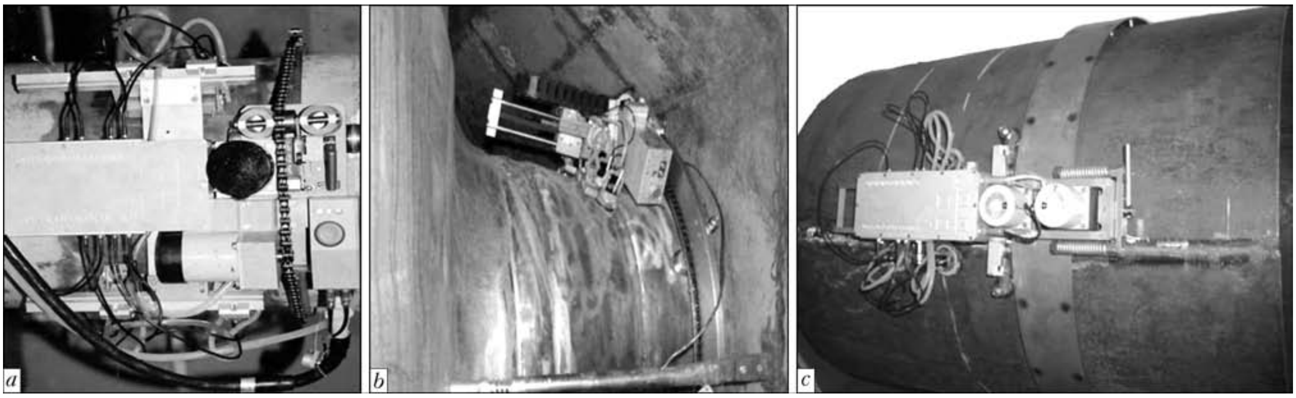


Figure 8. Scanners of «Avgur 5» series systems designed for testing Dn 300 pipelines on the examined object (*a*), Dn 500 nozzles of reactor body on the examined object (*b*), pipe on Dn 800 pipeline (*c*)

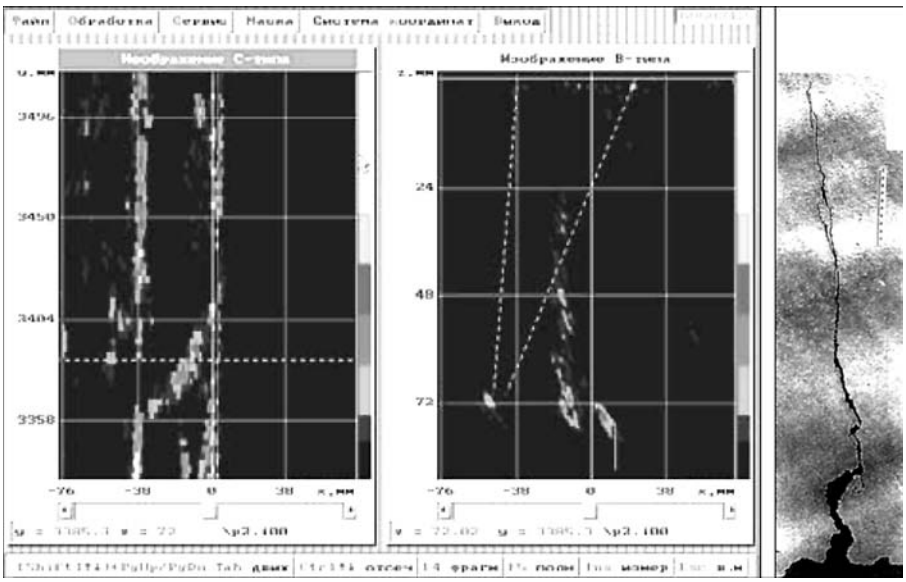


Figure 9. Image of a defect in #111 welded joint (PET angle of incidence of 40°)

conducting its in-service inspection. At development of testing procedure for this welded joint it was necessary to ensure the validity of diagnostics on the modern level. This is achieved by application of automated ultrasonic testing system of «Augur» series, providing recording and long-term storage of testing results, and using different methods of test data processing and presentation. This instrumentation allows detection of defects in the welded joint with determination of their geometrical dimensions and location coordinates.

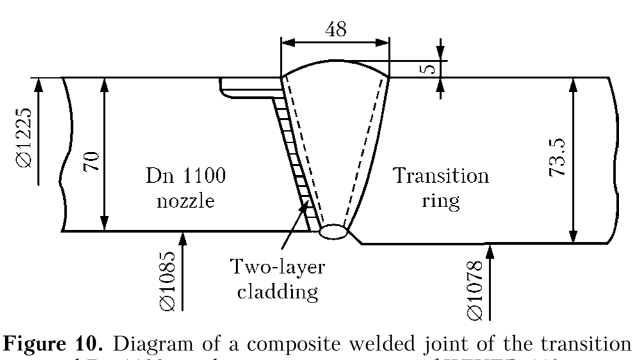


Figure 10. Diagram of a composite welded joint of the transition ring and Dn 1100 nozzle in steam generators of WWER-440 reactor plant

Figure 11 gives an example of a longitudinal crack image (coherent images of B, C, D types) obtained in the mode of instrumented control. The defect is localized on the base metal–two-layer cladding interphase. The image was obtained using PET of longitudinal waves applied to the welded joint from the side of Dn 1100 nozzle.

Examination of difficult-of-access structures, in which potentially dangerous locations were revealed by the results of AE diagnostics, and more precise assessment of the parameters of defects found in the weld and body of the pipe are performed with application of ultrasonic flaw detection tomographic unit SK-RDM developed by ETC «Welding and Inspection» together with RDM Company (Kishinev) (Figure 12). This instrument determines with a high degree of accuracy the dimensions of the configuration and coordinates of defects. It should be noted that it is the most successful implementation of A.K. Gurvich's idea about monitoring the quality of acoustic coupling. Presence of a convenient 3-dimnesional ultrasonic sensor of the transducer position in the instrument allows ensuring the object scanning path specified by the procedure, and reconstruction of two- and three-dimensional tomographic images of the defect.

Real-time automatic interpretation of the results is performed. Owing to multiprogram organization, SK-RDM may contain up to eight independent virtual specialized ultrasonic testing instruments, including those for testing austenitic welded joints with automatic adjustment for the features of ultrasonic vibration propagation in the crystalline structure of the weld. Supplied together with SK-RDM is a special program designed for receiving the testing results, their presentation in a convenient and easy-to-read form, maintenance of electronic data bases and obtaining information on item quality.

In order to assess the level of an object performance, it is not always sufficient to know the defect form, dimensions and coordinates. Residual stresses, present in different structural elements, primarily in the defect zone, have a considerable influence on SSS level.

Known are a multitude of devices for evaluation of residual stresses based on measurement of different characteristics of magnetic, electromagnetic or ultrasonic fields. Their common drawback is a very low accuracy of measurement (20–25 %). ETC «Welding and Inspection» of the N.E. Bauman MSTU together with «Intellekt» Ltd. (N. Novgorod) developed a sample of automated acoustic system «Astron» (Figure 13) designed for evaluation of structural and strength characteristics of materials. System operation is based on analysis of the connection between spectrum parameters of elastic wave pulses propagating in the studied material, and its physico-mechanical and structural characteristics.

Elastic wideband acoustic pulses are applied to the material of the studied part or element. Central spectrum frequency is selected in the range of 1–15 MHz, depending on material type. Depending on the studied material thickness, either bulk or non-uniform waves are used for analysis, they having 10–12 times higher sensitivity compared to the known wave types. At acoustic pulse propagation it interacts with the main components of material structure, namely grains, microcracks, micropores, internal stresses which influence the signal spectrum. During performance of a set of learning experiments, correlation or functional relationships are established between the spectral-acoustic parameters and structural-mechanical characteristics of the material of the proposed object of examination. The measurement algorithm is based on the method of determination of time delays appearing

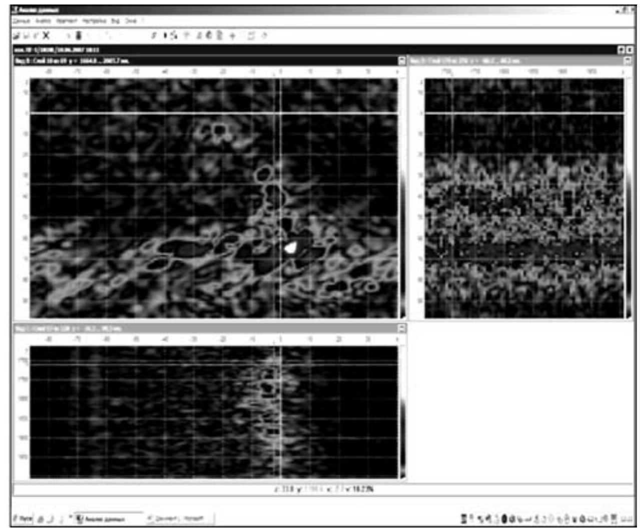


Figure 11. Coherent image of a plane defect obtained from the data of instrumented control using longitudinal waves

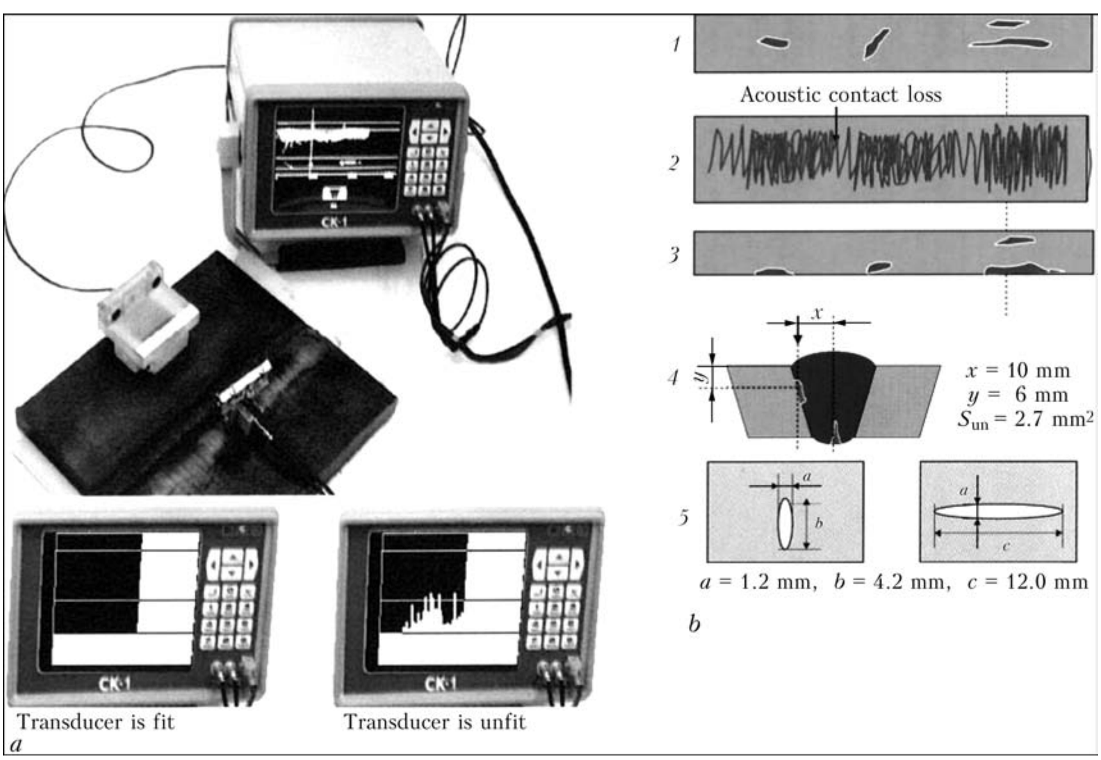


Figure 12. Multiprogrammed portable ultrasonic flaw detector SK-RDM: *a* — system self-control; *b* — defect information; *1* — top view; *2* — scanning trace; *3* — longitudinal weld section; *4* — transverse weld section; *5* — tomographic image of the defect

Figure 13. Portable spectral-acoustic system «Astron» for mechanical stress monitoring

in the equations correlating the velocities of propagation of elastic waves with the acting elastic stresses. Two pulses are selected which have traveled along different acoustic paths. The delay used in the acoustoelasticity algorithm, is calculated by the following formula:

$$\tau = \tau_0 - \frac{1}{2K}\sum_{i=1}^{k}\frac{1}{f_1}\,[\mathrm{arctg}\,[B_2(f_1)/A_2(f_i)] - \\ - \mathrm{arctg}\,[B_1(f_1)/A_1(f_1)]], \quad (1)$$

where τ_0 is the delay of the leading front of the second analyzed pulse; A, B are the sine and cosine members of Fourier transform, respectively; f_i is the i-th spectral frequency from the selected informative frequency range; K is the total number of spectral frequencies.

In order to determine stresses in the studied object, the required delays are measured and stresses are taken from the database in keeping with the earlier derived acoustoelastic dependencies.

Production trials of «Astron» system demonstrated its high efficiency at examination of structures, the material of which has a low degree of anisotropy, for instance 17G1S steel.

Figure 14. Measurement of the level of mechanical stresses in the pipe body at pit testing of a gas pipeline branch

For items from anisotropic materials (for instance, austenitic steels) the most effective NDT method is that of X-ray diffractometry based on the dependence of the law of diffraction and Hook's law. The method is based on experimental measurement of crystalline lattice deformation ε_1 of the totality of controlled metal grains, i.e. on measurement of crystalline lattice deformation $\Delta d_i/d_i$ in the specified direction.

Values of interplanar spacings d_i are related to angle of diffraction θ and wave length λ of the used monochromatic radiation by the law of diffraction:

$$2d\sin\theta = \lambda. \quad (2)$$

Deformation in this direction equal to the relative change of interplanar spacings, can be determined by the change of the angle of diffraction, if relationship (2) is differentiated:

$$\varepsilon_i = \frac{\Delta d_i}{d_i} = -\,\mathrm{ctg}\,\theta\Delta\theta_i. \quad (3)$$

Using equations of Hook's law for the planar stressed state, which is true for the subsurface layers (10–30 μm from the surface for steels) within the depth of soft X-ray penetration, we obtain an equation for determination of stresses σ_φ in azimuth direction φ:

$$\sigma_\varphi = \frac{E}{1+\nu}\,\mathrm{ctg}\,\theta\ \ (\theta_{\varphi,\,\psi=0^\circ} - \theta_{\varphi,\,\psi=90^\circ}), \quad (4)$$

where E is the Young's modulus; ν is the Poisson's ratio; ψ is the polar angle between the normal to the object surface and normal to the reflecting planes (assigned by the strain gauge collimator design).

A correspondence between «mechanical» and «X-ray» macrostresses (or stresses of the 1st kind) is observed for all the isotropic fine-grained (0.1–30 μm grain size) materials, provided the Hook's law is fulfilled. The true acting or residual microstresses are determined in polycrystalline metals and ceramics right up to ultimate strength.

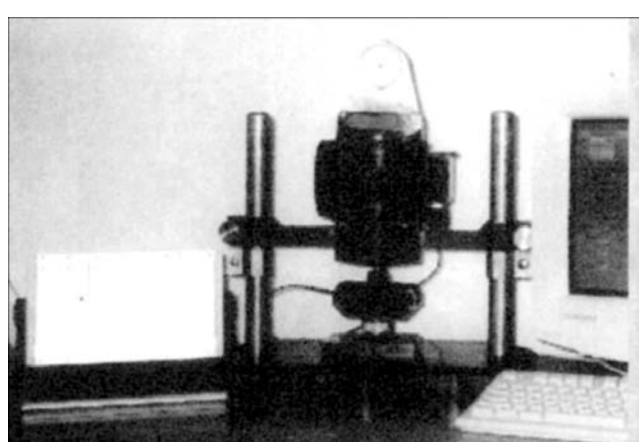


Figure 15. PIM-DV1 instrument

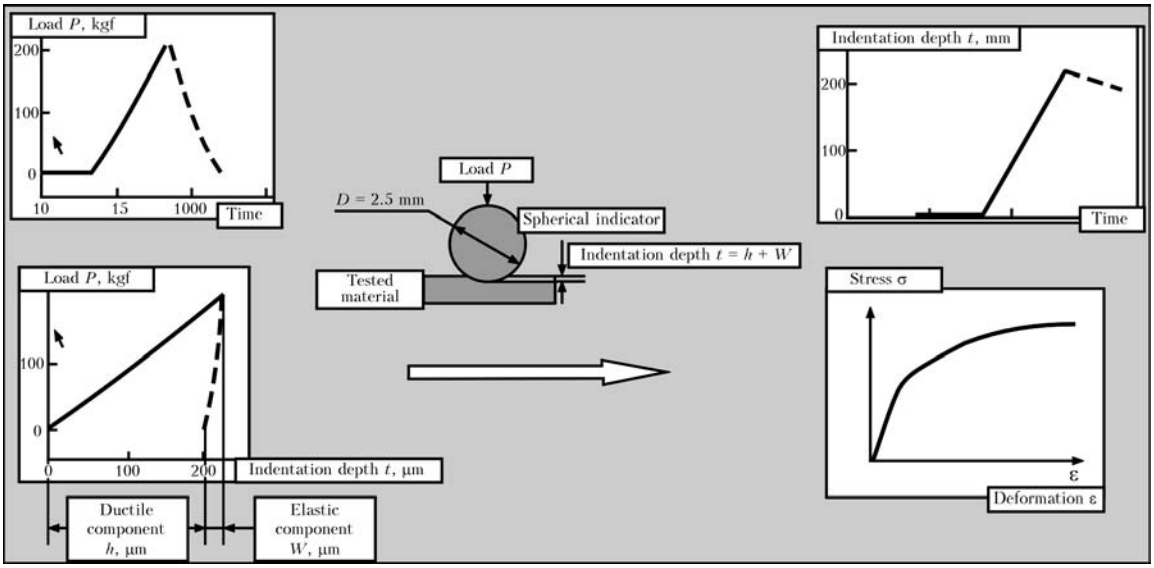


Figure 16. Schematic of determination of material mechanical properties based on the method of recording the diagram of elasto-plastic application of a spherical indentor

One of the most perfect X-ray diffractometers is the unit of «Molniya» Company SPC designed under the leadership of Prof. V.V. Kononov (Figure 14).

At the N.E. Bauman MSTU Prof. E.L. Makarov and Prof. A.S. Kurkin developed a calculation method for SSS determination for metals with brittle ($K_{IC} \leq \leq 120$ MPa) and tough-brittle fracture ($K_{IC} > > 120$ MPa). For the first metal group SSS calculation is performed by the methods of linear fracture mechanics, for the second group the criterion of limit ductility δ_{lim} is used. At the final stage of evaluation of the structure residual life, it is necessary to obtain the true picture of physico-mechanical properties of the metal (degradation) because of material ageing. Used with this purpose is PIM-DV1 device developed at SPA «Robotest» (Figure 15). The instrument performs real-time recording of the diagram of the local elasto-plastic deformation of the material in the coordinates of load–time, displacement–time and load–displacement at continuous application of a spherical indentor (Figure 16).

Results of modern theoretical and experimental investigations of the process of elasto-plastic application of the spherical indentor, allowed establishing the earlier unknown regularities of contact deformation, deriving the versatile and reliable criteria of strengthening and plastic deformation at indentation, establishing the conditions of physical similarity of the deformed state of different materials under the indentor, proposing the determining relationships between the force and deformation parameters of indentation and tension diagrams.

On this basis procedures of determination of the following mechanical properties: yield point $\sigma_{0.2}$, ultimate strength σ_t, strengthening curve, uniform deformation, relative elongation δ and relative reduction ψ, including the characteristics of Brinnel HB, Vickers HV and Rockwell HRC hardness, were developed for carbon, low-alloyed and high-alloyed steels in different structural conditions, as well as for non-ferrous metals and alloys.

The data for sections 1, 2 and 3 (see Table 1) are entered into «Resurs» software package, which also incorporates a data bank of crack resistance criteria, parameters of the equation of fatigue crack growth rate (ε_{ic}). This package also includes data on welded structure material properties. In addition to the numerical data, the bank includes regression models for forecasting the lacking crack resistance criteria depending on chemical and phase composition.

Many years of experience of our Center allowed elaboration of the «Rules of evaluation of the residual life of welded main gas pipelines by monitoring results» and conducting their experimental verification. A good agreement of the design and experimental data was established.

METALLURGY OF ARC WELDING OF STRUCTURAL STEELS AND WELDING CONSUMABLES

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Review is made of the results of investigations, carried out at the E.O. Paton Electric Welding Institute, on the problems of metallurgy of arc welding of structural steels and development of welding consumables. Problems of arc stability and electrode metal transfer, evaporation of metal and slag, formation of aerosols, interaction of metal with gases and problems of porosity, modeling of interaction in multi-component systems, such as metal–gas, metal–gas–slag, chemical inhomogeneity, crystalline cracks, non-metallic inclusions in welds are described. Investigations of systems of alloying and prediction of weld metal microstructure were made, problem of formation of hydrogen-induced cold cracks in welded joints of high-strength low-alloy steels is elucidated. The achievements of the Institute in the development of new welding consumables are shown and the trends of future research works are outlined.

Keywords: *metallurgy of arc welding, structural steels, welding consumables, weld, arc stability, welding aerosol, interaction of metal with gases, porosity, non-metallic inclusions, alloying systems, prediction of microstructure, hydrogen-induced cold cracks*

Over the whole many-year history of formation and development of the E.O. Paton Electric Welding Institute, the continuous and unremitting attention was paid to the research and development of welding consumables, creation of industrial technology and their implementation in industry.

Development of coated electrodes for manual arc welding commenced at the Institute since 1935. The processes of arc stabilization were studied and electrodes were developed with a stabilizing thin coating for DC and AC welding, that allowed increasing the welding efficiency as compared with that using chalky-coated electrodes. Results of pre-war research works in this direction are summarized in works [1–3]. Even in the first years of existence of the E.O. Paton Electric Welding Institute the mechanization of welding was considered as its most important task.

During 1939–1940, the method of submerged arc welding was developed under the supervision of Evgeny O. Paton [4]. The first fused flux AN-1 was developed in 1940 [5]. It was used in combination with a silicon-manganese wire. The production of this flux was organized at the «Proletarij» plant in Donbass. In 1941 a high-manganese flux AN-L was developed.

The submerged arc welding was greatly progressing in the years of the Great Patriotic War. Under supervision of E.O. Paton the new welding consumables (fluxes AN-2, AshA and AshMA, and also appropriate electrode wires) and technologies of automatic welding of armor steel, allowing creation of the production line for manufacture of armored bodies of tanks, bombs, artillery systems were developed.

Alongside with large and intensive works at the defence plants, the staff of the Institute continued to carry out the research works. In 1942, V.I. Dyatlov discovered the phenomenon of self-regulating the electrode melting in submerged electric arc welding [6]. Results of investigations of this phenomenon by B.E. Paton in collaboration with A.M. Makara, P.I. Sevbo, M.N. Sidorenko allowed them to design a portable, simple and reliable welding automatic machine and to use the simplest AC power sources.

Owing to automation of the welding process, it was possible to increase abruptly the volumes of manufacture of tanks and to increase the quality of welded joints.

During the war and first post-war years Boris E. Paton carried out a number of important investigations of submerged arc welding [7–17], devoted to study of processes of heating and melting of electrodes, sizes of electrode drops, stability of arc burning, self-adjusting of arc in consumable electrode welding. Static properties of automatic machines for submerged arc welding were investigated, procedure of analysis of operation of automatic machines by static volt-ampere characteristics was suggested. B.E. Paton showed that the optimum properties are characteristic of the automatic machine with a continuous rate of wire feed, equipped with power sources with a quick-response controller of voltage. This conclusion served as a basis for the design of equipment for mechanized submerged arc and shielded-gas welding.

During the post-war years Evgeny O. Paton organized the carrying out of investigations of electric, thermal and metallurgical features of the submerged arc welding process, the results of which were published in monographs, edited in 1946 and 1953 [18, 19]. Separate chapters of these monographs are devoted to the investigations of electric processes in submerged arc welding, principles of operation of welding heads, adjustment of submerged arc welding process [20–22]. Specifics of thermal and metallurgical processes in submerged arc welding, methods of effective protection of welding zone from air, metal interaction with gases and slag, methods of control of chemical composition and properties of weld metal, formation of non-metallic inclusions, metallurgical systems of fluxes and electrode wires, advanced fluxes for welding of low-carbon and alloyed steels and technology of their industrial production are described in separate chapters of these monographs.

In next works of the E.O. Paton Electric Welding Institute a large attention was paid to the investigations of metallurgical processes of submerged arc welding, namely: formation of pores, hot cracks and non-metallic inclusions, determination of weld pool temperature, study of characteristics of welding arcs, measurement of temperatures and determination of composition of gases, surrounding the arc, investigation of surface properties of welding fluxes and slags [23–39].

At high temperature of arc column, the main reactions should proceed at high rates providing the thermodynamic equilibrium [28]. This statement was used in calculation of reactions in atmosphere of arcs in submerged arc welding [29]. It was supposed that the weld pool temperature and specific heat content of metal in it are the function of thermophysical properties of metal that was confirmed in works [30, 31]. The investigations of metallurgical processes of submerged arc welding and surfacing and development of welding and surfacing consumables were also continued successfully during the next years [39–54]. Their results are generalized in monographs [34–38, 40, 42, 44, 48, 52, 53].

The rapid progress of machine building, construction and other branches of the national economy of the USSR during the post-war years required the development and investigation of the new methods of welding of structural steels of different classes using consumable electrode in shielding gases and their mixtures, solid and flux-cored wires. It was necessary to organize the industrial manufacture of coated electrodes of general and special purpose. The problem of improving the labor conditions of welders by the development of low-toxic electrodes became acute.

B.E. Paton initiated the investigations required for the solution of these problems. It was necessary to acquire more comprehensive knowledge in processes proceeding in welding arc, specifics of melting and transfer of electrode metal, processes of evaporation of metal and slags and formation of aerosols. It was also necessary to study the processes of interaction in metal–gas, metal–gas–slag systems, formation of porosity in welds, alloying of weld metal and control of its structure, hydrogen mass transfer in welded joints and formation of hydrogen-induced cold cracks (HICC). Below, the most important results of these investigations are described.

Arc stability and electrode metal transfer. The stability of arc burning and electrode metal transfer are mainly defined by electrophysical characteristics of an arc discharge, connected with composition and weight of coating (flux, wire), welding conditions and kind of current [55–62].

In real welding arcs the emission characteristics of electrode coatings and slags become primary significant. The coatings (slags), intensively emitting electrons, provide the higher arc stability and steady repeated ignition of AC arc at low values of ignition voltage [58, 60, 61].

The emission of positive ions is necessary for maintaining the electric conductivity in the near-electrode regions and compensation of volume negative charge near the cathode surface. Owing to compensation the thermoelectrons can participate in maintaining the electric discharge. The electronegative elements, added to the composition of welding consumables (for instance fluorine, oxygen, etc.), cause decrease in the intensity of electric field near the cathode. Here, the intensity of field in the anode region and drop of anode voltage grow, thus leading to the increase of penetration depth in case of welding using current at the straight polarity [129].

The electronegative elements in the arc atmosphere cause also strong constriction of arc discharge column. The estimates made on the basis of conceptions of local thermodynamic equilibrium in the arc column and channel model of a column have shown that decrease in temperature at the periphery of the current-conducting channel should lead to enrichment of this region with negative ions. The change in dimensions of an arc column by adding the electronegative elements to the composition of welding materials is an efficient way of control over the welding process parameters.

The transfer of an electrode metal, especially followed by short circuits of an arc gap, influences greatly the stability of arc burning. To estimate the arc stability and electrode metal transfer the statistic methods have been worked out [61]. The arc of an alternating current is burning stably if a reliable repeated its ignition is provided [13, 15, 16, 20, 25, 26, 62].

Many scientists studied the peculiarities of electrode metal transfer at different methods of arc welding [11, 12, 16, 39, 52, 55–58, 60, 61, 71, 72, 121 and others]. The theory of electrode metal transfer has been worked out and the analysis of forces influencing the drop of electrode metal was carried out [39, 58, 60]. The criteria of estimation of electrode metal transfer and stability of arc burning were suggested [58]. The relation between these criteria and technological characteristics of welding consumables was established.

The application of information-measuring systems (IMS) [59] allowed providing automatic acquisition and accumulation of information and its mathematical processing in real time, increasing many times the volume of obtained information and reducing simultaneously the duration of its processing.

A great deal of experimental material on the arc stability and metal transfer has been accumulated [60, 61]. A number of slag systems was investigated and compositions of slags were found providing an equal stability that allows prediction of arc stability during development of electrode coatings, fluxes, flux-cored wires, not using the experiments [131–133].

It is possible to increase the arc stability by adding of electropositive elements or lower metal oxides of a variable valence, forcing out the fluorides to the coating outer layer, reducing the SiO_2 activity in the slag and increasing the coating weight.

Adding of easily-ionizing elements to the coating, core of flux-cored wire or a flux leads to the increase in concentration of positive ions in the periphery region of an arc and decrease of its constriction due to the compensation of action of negative ions and also to the decrease of work function of electrons from the cathode. In this case, the necessary value of density of current of electrons, coming from the cathode, can be achieved at the lower values of intensity of electric field near the cathode.

The statistic approach, realized through the IMS, allows the probable estimating of effect of different factors (composition of welding materials, welding conditions, kind of current and polarity) on the formation of porosity in welded joints, caused by arc elongation, and also estimating the influence of inductance of welding circuit and shape of external characteristics of power source, executive mechanisms of automatic and semi-automatic machines on the metal transfer and stability of welding process.

Metal and slag evaporation, formation of aerosols. One of the ways to improve the labor conditions of welders is the development of low-toxic welding consumables. The hard component of a welding aerosol (HCWA) is formed at the condensation of metal and slag vapors. Conditions of evaporation of metal and slag have a decisive effect on the aerosol composition. The temperature of a drop, its specific surface and rate of manganese transition from a drop volume to its surface define the manganese concentration in the aerosol [63–68].

The arc elongation, increase in its specific surface of evaporation in drop refining leads to the more intensive manganese evaporation. The main source of manganese and iron enter to the welding aerosol is a metallic melt [94]. The presence of a slag film on its surface impedes the iron and manganese evaporation. The intensity of manganese evaporation from the molten slag is increased with the growth of basicity and content of manganese oxides in it [64]. The increase in welding slags basicity leads to intensification of evaporation of compounds of potassium, sodium, magnesium and calcium, here the bulk evolutions of HCWA are significantly increased. To decrease them, it is recommended to increase the content of structure-forming anions of silicon, titanium and aluminium in slags and to decrease the content of cations-modifiers, such as potassium, sodium, magnesium [65].

Nowadays, the maximum allowable concentration of elements in the air of working zone is established from the assumption that the welding aerosol represents a sum of simple oxides and compounds of elements. However this conception is not true. For example, manganese and iron can form different compounds: manganese in the form of $MnFe_2O_4$, $MnOSiO_2$, MnF_2 and others; the iron in the form of Fe_2O_3, $MnFe_2O_4$, K_3FeF_6 and others [66].

The toxicity depends greatly on the valence of manganese and chromium in the composition of aerosols, namely the higher their valence, the higher toxicity of HCWA.

The particles of welding aerosol have a complicated morphology and consist of a nucleus and shell. The nucleus composition includes mainly complex iron and manganese compounds like spinels, and shell composition includes complex silicates, fluorides. This structure of particles is characteristic of all welding consumables (solid wires, flux-cored wires, electrodes) [66]. This problem is examined in detail in works [67, 68]. To decrease the bulk evolution of welding aerosols is possible providing the control over the following factors: maintenance of a rated voltage of welding arc, improvement of slag protection of metal; decrease in slag basicity; decrease in content of volatile elements and their compounds in a slag melt (fluorine, potassium, sodium); application of inverter power sources, which limit the current growth at the short circuit and decrease the temperature of drops.

Interaction of metal with gases, porosity. These processes were studied in works [19, 23, 27, 29, 34, 40, 41, 44–46, 53, 69–76, 79–91, 93 and other] and generalized in work [121]. The gases absorption by a molten metal is defined mainly by the composition of an arc atmosphere, presence of a protected layer of slag and its properties, temperature of metal, kinetics of electrode melting and metal transfer. The mechanism of gases absorption by metal in arc welding has been studied. It is shown that the increase of gases content in weld metal in welding at current of a straight polarity is due to the lower temperature of drops [44]. The temperature of drops at a reversed polarity is higher, the evaporation of drops metal increases, partial pressure of gases at the metal–gas boundary decreases [16, 44, 121–125]. The gases solubility in metals and its temperature dependence are really important. Review of investigations of nitrogen and hydrogen solubility in metals and alloys is given in works [79, 126].

The type of temperature dependence is defined by the condition of atmosphere, with which the gas is in contact. When contacting the usual atmosphere under the conditions of thermodynamic equilibrium the maximum hydrogen content is observed at temperature 2600 K, while in heating up to higher temperatures it is decreased due to intensive metal evaporation [126]. As calculations showed [122–125], at iron contact with hydrogen-containing plasma the hydrogen mass content is decreased monotonically with increase in temperature. This is probably due to the fact that during absorption of gases from the usual atmosphere the limiting link is the dissociation of gas molecules near the metal surface. In the process of absorption from the plasma of arc discharge the level of dissociation is defined by the arc temperature, which weakly depends on the temperature of metal surface [121].

As calculations showed, in the larger part of arc column section HF and OH are completely dissociated. With decrease in the arc temperature the effectiveness of hydrogen binding with fluorine or oxygen is growing, as at equal pressures HF and OH have equal level of dissociation at temperatures differed approximately by 1000 K [121, 123, 130].

The hydrogen dissolution in metal of drops and weld pool is hindered by its binding with fluorine. The presence of HF in the arc atmosphere was experimentally proved [75]. The fluorine binding in the arc atmosphere into compounds with alkali-earth metals decreases the possibility of HF formation and contributes to increase of hydrogen content in the weld metal [29, 34, 41]. Adding of carbonates or higher oxides of manganese and iron to the electrode coating, ceramic flux and core of a flux-cored wire or oxygen to the mixture of gases leads to the decrease in a partial pressure of hydrogen in arc atmosphere and hydrogen content in the weld metal [23, 29, 34, 40, 41, 44, 46, 69, 76, 79, 84, 90, 98, 121].

To prevent the nitrogen absorption, the reliable gas and slag shielding of molten metal of a drop and a pool is created. The process of metal interaction with nitrogen under welding conditions is considered in works [78–81]. It was found that a slag melt exerts a significant diffusive resistance against nitrogen absorption by metal from the gas phase. The gas evolution from a slag melt increases the efficiency of shielding the molten metal from the contact with atmosphere.

The providing of gas-slag shielding for the molten metal in open arc welding using electrodes and flux-cored wires depends on kinetics of dissociation of gas-forming components of a core coating, volume and surface properties of a slag melt. The calculated-experimental method of prediction of the process of gas evolution from the core at the high heating rate [79] and the physical model of metal interaction with gases [80, 81] were developed. It was established that the solidification conditions of a weld pool have a great influence on the final content of gases in the weld metal [44, 82].

The character of hydrogen redistribution between the weld pool and solidified metal is defined mainly by a solidification rate. At the solidification rate of the pool, typical of the main processes of arc welding, the diffusion processes are suppressed to a large extent, the hydrogen content close to its average content in the weld pool is observed in the weld metal. The nitrogen is less diffusely-mobile element than hydrogen, therefore its diffusion redistribution in the process of solidification of a weld pool is even less probable.

The increase in the rate of the pool solidification leads to redistribution of hydrogen in the deposited metal; the content of residual hydrogen, retained by metal, is increased and the mass fraction of diffusive hydrogen is reduced. It is attributed to the changes in metal structure, degree of lattice intensity and appearance of the developed lattice of dislocations [44, 69].

The hydrogen in welds is located in an oversaturated solid solution, inclusions and vacancies. The investigations of hydrogen diffusion mechanism in welds were carried out. It was found that hydrogen is characterized by abnormally high diffusion mobility in metal as compared with other interstitial impurities. The experimental determination of a concentration field of hydrogen in welds is connected with large methodical difficulties [82]. During recently, the numerous methods found a widespread, realization of which requires a reliable information about the temperature-concentration dependencies of parameters of hydrogen diffusion in different zones of the welded joint. The application of chromatographic method [83, 84] allowed the development of procedure of calculated-experimental determination of a coefficient of hydrogen diffusion in welds and steels at 20–200 °C [85]. The new data have been obtained about the effect of weld metal alloying by manganese, nickel, molybdenum, chromium on diffusion mobility of hydrogen [91]. The influence of stresses and strains on the hydrogen permeability and hydrogen diffusion in metal was studied [86].

The high diffusion mobility of hydrogen in welds, made by highly-basic welding consumables, as compared with rutile consumables, is due to a smaller amount of «traps», trapping hydrogen [127, 128].

The most important problem of arc welding is the prevention of welds porosity. The gases compositions, evolving from the weld pool in submerged arc welding of steel, and their influence on welds porosity have been studied. It is shown that except of carbon oxide, the pore initiation can be provoked by hydrogen and nitrogen evolution from the solidifying metal. The composition of gases was determined and the hydrogen pressure in pores was evaluated [87, 88], the kinetics of initiation and growth of gas bubbles in weld pool was studied [44, 82, 121].

It was revealed, that the probability of pore nucleation will be higher for the gas, at which the metal has a lower interfacial tension σ_{m-g} on the gas–metal interface. The increase in the interfacial tension here and deterioration of substrate wettability by metal promotes the formation of stable gas nuclei. This is, probably, due also to the fact that the well-deoxidized metal of weld pool, as compared with a poorly deoxidized one, is capable to trap a smaller amount of gases [44]. The absence of a noticeable oversaturation is the evidence of heterogeneous mechanism of pores formation in welds. The reason of porosity in welding using electrodes with rutile and ore-acid coatings and flux-cored wires of similar type is the hydrogen evolution mainly [44, 69, 72], which diffuses into the gas bubble from the molten and solidified metal. Adding of deoxidizers into the coating and weld pool impedes the desorption of hydrogen from the pool, making the process of degassing longer. In this case the efficient method of porosity prevention is the intensification of the gas evolution process [44, 69]. The viscosity of a welding slag has no significant influence on the weld resistance to the pore formation [34, 40]. The prevention of porosity, caused by hydrogen, is achieved due to the reduction of hydrogen content in the coating (flux) applying high-temperature calcination, removal of coating elements containing the crystallization moisture, the selection of compositions of coating (flux), providing the hydrogen binding in the arc by fluorine or decreasing its partial pressure, improvement of shielding properties of slags, increase in the coating mass, use of a two-layer structure of electrode coating or flux-cored wire [44, 52, 70, 121].

Modeling of interaction in multi-component metal–gas and metal–gas–slag systems. The physical model of gas saturation of metal surface layer, contacting the low-temperature low-ionized plasma, has been developed. The model is based on the kinetic theory of gases and accounts for motion of ions, atoms and molecules in the plasma volume, absorption and desorption of gas on the metal surface, interaction of sorption and desorption flows of gas near the metallic surface, and also diffusion transfer of molten element in the metallic melt.

Basing on the physical model, the mathematical model has been created which allows calculating the parameters of process of gas absorption in metal depending on the plasma characteristics, heat duration, partial pressure of impurity in the gas, temperature and other factors. To solve the system of equations of a mass transfer, the numerous methods were applied. The calculations have been carried out to reveal the peculiarities of nitrogen and hydrogen absorption by iron from the plasma, containing nitrogen and hydrogen as an impurity. The activation of molecules of nitrogen and hydrogen in plasma (exciting, dissociation, ionization) changes qualitatively the kinetics of their absorption by a melt as compared with the equilibrium conditions: the dissolution rate increases by several orders, it exponentially depends on the plasma temperature, and linearly — on the partial pressure of hydrogen [121–125].

The algorithm of thermodynamic description of high-temperature processes in multi-component heterophase metal–gas–slag-systems has been developed. The computer program has been created which is intended for the numerical estimation of influence of temperature, pressure and initial element composition of the system on the equilibrium composition of interacting phases. Here a great variety of chemical reactions is taken into account, which take place between the large amount of chemical compounds, included into composition of reacting phases, as well as in evaporation, condensation, dissociation, etc. [90].

The thermodynamic analysis of ways of decreasing the hydrogen content in the molten steel during the change of compositions of slag and gas phases under the welding conditions in CO_2 showed that the efficient way of decrease of hydrogen content in molten metal is the adding of SiF_4 to the gas phase (in practice it can be achieved through the adding of silicon fluorides into the coating of electrodes and core of a flux-cored wire), and the increase in an oxidizing potential of gas and slag phases does not lead to the significant decrease in a mass fraction of hydrogen in the molten metal.

The thermodynamic approach was used in the development of self-shielding flux-cored wires on the base of oxyfluoride systems [92]. The shielding of molten metal from the absorption of air nitrogen is attained by oxidization of magnesium and aluminium in the wire core and exchange reactions of oxides with fluorides.

The results of many-year investigations of the processes of interaction of metal with gases and formation of porosity in welds are generalized in monographs [29, 34, 40, 44, 121].

Chemical heterogeneity, crystalline cracks. The studies of initial crystallization and microscopic heterogeneity of welds were very important for the development of advanced welding consumables and effective technology of welding [100–108]. The regularities of elements liquation in metal of welds on steels have been studied and systematic quantitative data about the influence of carbon, manganese, sulphur and silicon on dendrite, zonal and layer liquation of manganese, silicon and sulphur in welds have been obtained [109–115]. The ways of reducing the dendrite liquation of sulphur were suggested. It was found that the level of harmful effect of segregating sulphur and phosphorus impurities on the low-temperature brittleness of weld metal depends mainly not on their total content, but on the level of phosphorus segregation in the grained structure of a weld metal, size, shape and nature of distribution of sulphide inclusions [48, 77, 111, 112, 115].

The methods of increase in cold-resistance of welds have been developed. It is necessary to limit maximally the phosphorus segregation in austenite grain by control of its redistribution in the primary structure (by additional microallying), and to decrease the amount and size of oxysulphides in the center of an austenite grain by decrease in oxygen content in a weld. Coming from the applied alloying system and the system of deoxidization, it is necessary to distinguish impurities by the degree of their negative effect on cold resistance. Using the alloying systems containing nickel or chromium, the main attention should be paid to the phosphorus content; in case of increased oxygen content the sulphur impurity is undesirable.

To investigate the liquation processes occurring in the weld pool and welds, the new method was suggested to estimate the chemical heterogeneity of weld metal [113]. According to data of X-ray microanalysis the maps of distribution of concentrations of separate elements are made. The statistic processing of information, presented on the concentration maps, allows the establishing of parameters of chemical heterogeneity. Using this method, the alloying system Ni–Mn was studied, and also the optimum content of these elements in welds was established.

Non-metallic inclusions. The laws of redox reactions are predetermined by physic-chemical properties of coatings (fluxes), their deoxidization potential and basicity of formed slag, characteristics of melting and transfer of electrode metal, regularities of diffusion kinetics, which define the limiting links of reaction proceeding. The total rate of redox reactions is limited by the rate of diffusion transport of reagents to the interphase surface. On this basis, the calculation schemes of oxidation or reduction of element in welding were plotted [36]. The products of redox reactions are non-metallic inclusions of endogeneous type, which are formed in metal of weld pool and weld.

The peculiarities of proceeding the redox reactions of manganese and silicon depending on the electrode coating composition and their effect on content, composition, shape, dispersity of non-metallic inclusions and mechanical properties of a weld metal are described in works [36, 40, 94, 95]. In [40, 69, 96, 97] the negative role of silicon-reduction process in decrease of ductility and impact strength of a weld metal is shown. The optimum content of silicon, providing the maximum structural and chemical homogeneity of welds was determined [95].

Inclusions may serve as nuclei of an acicular ferrite, the large fraction of which in weld structure is attributed usually to the high impact toughness. The presence of lower oxides of titanium and aluminium on the surface of inclusions promotes the ferrite origin. As the results of investigations showed [163], the region with an increased dislocation density ($\rho = 1\cdot10^{12}-1\cdot10^{14}$ cm^{-2}) is formed around inclusions of type of alumosilicates or titanium oxides, having a laminar structure. This leads to fragmenting of the forming structure into stages of incubation period of its origin, i.e. regions with a low density of dislocation ($\rho = 1\cdot10^{10}$ cm^{-2}) are separated by areas having a high ($\rho = 1\cdot10^{14}$ cm^{-2}) density of dislocations. In these zones of the primary grain the structure of an acicular ferrite type is formed. The fine-dispersed inclusions of a homogeneous composition and large inclusions of manganese silicate type are surrounded by a solid solution with a much lower density of dislocations ($\rho < 1\cdot10^{10}$ cm^{-2}). In this case a polygonal ferrite is formed within the primary grain. It was established that to form the weld of a high level of toughness it is necessary to keep a definite balance between the content of oxygen and deoxidizers in metal of welds [164].

Using the thermodynamic calculations, different methods of sulphur removal from the molten iron were analyzed [98]. It was found that this can be most effectively realized by using slag of a high sulphide capacity. Study of kinetics of process of sulphur transition from metal into slag showed that it is possible to create such conditions in welding at which the high desulphurization of metal is possible even during a short period of time as compared with the existence period of the weld pool. Experiments, made on test samples of flux-cored wires, confirmed these theoretical conclusions.

Until now, there is no a generally-recognized opinion about the mechanism of effect of inclusions on the process of structure formation. In this connection, the future investigations are required concerning the role of inclusions in origin and epitaxial growth of ferrite on some crystallographic planes with a small misfit of lattice parameters of surface of inclusions and ferrite; development of methods of assurance of optimum size of inclusions, constant required composition of aluminium and titanium in welds and optimum content of oxygen and deoxidizers in metal of welds; thorough study of mechanism of origin of non-metallic inclusions, including physical and mathematical models of this process; the further investigations of physical-chemical structure of slag systems from the point of their effect on the formation of nuclei of inclusions and role of inclusions of size of about 10 μm in the formation of structure of welds [99]; development of metallurgical methods of binding of manganese sulphides and sulphur as a whole into compounds, differing greatly by lattice parameters from ferrite.

Investigation of systems of alloying and prediction of microstructure of weld metal. Recently, a great attention is paid to the study of interrelation between composition, structure and mechanical properties of metal of welds and joints. This was caused by the need in the development of materials for welding of low-alloy high-strength steels. The investigations of this interrelation were carried out on the example on multi-layer welds, in which three typical structural zones can be distinguished: coarse-grain, fine-grain and columnar. In Ni–Mn alloying systems, used in welds of structures, operating at low temperatures, the increase in cold resistance of weld metal is attained by the formation of an acicular ferrite, decrease in a carbide fraction, removal of pearlite, refining of particles of the second phase in the zone of a columnar structure of heat-treated beads, decrease of a relative area of coarse-grain zone to 10–15 % and formation of grained bainite in it [116]. This structure is attained owing to alloying of weld metal by nickel and manganese, wt.%: 0.5–0.7 Mn; 3.0–3.2 Ni or 1.1–1.3 Mn; 2.1–2.3 Ni. Here, the zone of columnar structure represents a structure of an acicular ferrite, and the second phase is presented by islands of a residual austenite and small amount of fine carbides.

The application of high-strength steels for manufacture of welded structures, operating under extreme conditions, required the optimizing of microstructure and mechanical properties of weld metal. The content of alloying and microalloying elements (manganese, nickel, molybdenum, chromium, boron, magnesium) varied within the wide range to produce the weld metal having the yield strength from 450 up to 900 MPa.

It was established that characteristics of mechanical properties of weld metal are defined by several factors: quantitative ratio of acicular, grain-boundary ferrite and ferrite with a second phase; dispersity of the second phase, its type and morphology, non-uniformity of distribution of its particles; micro-non-uniformity of distribution of alloying and impurity elements. The required strength and impact toughness of metal of multi-layer weld with yield strength of up to 600 MPa is attained at content of acicular ferrite in weld metal of not less than 70–80 vol.% and presence of uniformly distributed islands of the second phase with a martensite-austenite structure in the zone of a columnar structure of alloying systems Mn–Ni and Mn–Ni–Mo (up to 0.2 wt.% Mo). In case of alloying system Mn–Ni–Mo (yield strength of metal up to 800 MPa) the increase in strength characteristics of a multi-layer weld, preserving high cold resistance, occurs due to increase in a volume fraction of the equiaxial second phase (islands with martensite-bainite-austenite structure) and uniformly distributed dispersed carbides. Here, it is necessary to keep a constant content of an acicular ferrite.

Microalloying by manganese and boron increases the impact toughness of the weld metal owing to change in dispersity of the second phase, and also degree of chemical micro-inhomogeneity by nickel and manganese. Effect of microalloying is explained by the reduction in temperature of austenite transformation and increase in its stability. With Mn–Ni–Mo–Cr system of alloying the microalloying by boron and magnesium is not effective.

Over the recent years the more and more attention is paid to the control of structure and properties of weld metal by changing the oxygen potential of fluxes [136]. The effect of this characteristic on the degree of alloying of solid solution by manganese and titanium [134, 135, 137, 138] and also on carbon content was studied.

The experimental investigations of systems of alloying of weld metal are long-time and labor-intensive, therefore, it is rational to make calculations and prediction of microstructure of weld metal [117, 118]. The basis of calculations served a physical model of formation of microstructure of low-carbon low-alloy metal, suggested in work [119]. The model allows accounting for ways of formation of microstructure: growing-in of needles-plates of Widmanstaetten ferrite across the entire grain and «to pin» needles-plates as a result of their interaction with acicular ferrite originated on inclusions distributed in the austenite grain body.

The rate of growth of different modifications of ferrite is determined from calculated thermokinetic diagrams. Using these diagrams, the temperature-time ranges, within which the above-mentioned growth takes place, are also determined.

The developed computer program [120] using the preset chemical composition of weld metal allows calculating the isothermal diagrams of austenite decomposition and determining the temperature of the austenite decomposition beginning under conditions of continuous cooling by superposition of a thermal cycle curve on this diagram, thus calculating the volume fractions of different microstructure components. The results of calculations are used for study of effect of parameters of welding processes, chemical composition of weld metal, sizes of the primary austenite grain on ratio of microstructure components of weld metal.

The comparison of results of calculations and experimental data showed that the method of calculation allows evaluating of structure changes connected with effect of conditions of solidification, chemical composition of weld metal and other factors. The application of units «Gleeble» gives an opportunity to combine successfully the experimental study and mathematical modeling of austenite transformation in welds of low-alloy steels [139].

HICC in welded joints of high-strength low-alloy steels. Over many years the investigations of mechanism of cold crack formation, including HICC, are carried at the E.O. Paton Electric Welding Institute. The kinetics of distribution of hydrogen in welded joints, effect of stress raisers, mechanisms of a delayed fracture and hydrogen embrittlement [143–152, 155–158], as well as formation of hydrogen brittleness in metal with bcc-lattice [140–142, 153, 154, 159–162] were studied.

The developed methods of determination of diffusive hydrogen content were put into basis of the International Standard. To evaluate the effect of conditions of deforming and traps on the nature of mass transfer of hydrogen, the investigations of diffusion and transport of hydrogen in metals, welds and welded joints were carried out. Hypothesis was suggested and physical model of hydrogen embrittlement of steels and welds was developed; methods were developed for evaluation of hydrogen effect, which were based on advanced conceptions of metal physics on the mechanism of brittle fracture of steels.

Review of investigations, carried out at the E.O. Paton Electric Welding Institute, on the problem of hydrogen presence in welded joints, is given in works [121, 127, 128], which after analyzing allow making the following conclusions [121]:

1. Risk of HICC formation can be evaluated using the calculation of carbon equivalent C_{eq}, characterizing the level of steel alloying. Numerous technological samples, sufficiently well reflecting the behavior of steels in welding, allow evaluating the integrated effect of factors, causing the crack formation.

2. Susceptibility to HICC formation depends on steel microstructure. For example, twin martensite is much more sensitive to embrittlement than self-tempered low-carbon martensite.

3. Normal temperature is most favorable for HICC formation.

4. Cold cracking depends on the rate of deformation of welded joint: the higher rate of loading, the lower level of embrittlement.

5. The main link of hydrogen embrittlement mechanism is the behavior of initiating microcrack, occurring in the process of deformation in the presence of hydrogen. Localization of a negative charge on adsorbed

atoms of hydrogen leads to the reduction in level of a normal stress, required for the microcrack transition to the autocatalytic propagation in the field of stresses that is considered at the macrolevel as an effect of embrittlement.

6. The most important factors are the evolution of dislocation structure in plastic deformation, and also properties of grain boundaries, particles of the second phase and non-metallic inclusions. A special role of dislocations in mechanism of hydrogen brittleness is distinguished by the fact that their displacement is the main mechanism of the plastic deformation and, simultaneously, the most effective method of hydrogen transport in the volume of metal [140–142].

7. Non-metallic inclusions, depending on their relation with a matrix, can behave from the very beginning of deforming as cracks, and the brittle inclusions are capable themselves to initiate the sharp cracks.

8. The presence of hydrogen in weld metal and HAZ reduces a specific energy of surface of a submicrocrack. Decrease in stress of a brittle fracture, initiated by a submicrocrack, occurring by a dislocation scheme, is proportional to the decrease in a specific surface energy of metal under the influence of hydrogen.

9. Cold cracking in welding of structural steels is the complicated and specific process. An important role in it is played by hydrogen, available in weld metal and HAZ. It is possible to decrease the susceptibility of the welded joint to cold cracking by adding hydrogen traps into the weld metal. These traps are the different structure defects, such as vacancies, dissolved atoms, dislocations, boundaries of grains and phases, micro- and macropores, non-metallic inclusions, particles of the second phase, etc. Hydrogen traps may be fine-dispersed non-metallic inclusions, uniformly distributed in steel structure, and residual austenite.

New welding consumables. Development of welding consumables and technologies of their manufacture was carried out on the basis of many-year investigations of fundamental problems of metallurgy of arc welding at the E.O. Paton Electric Welding Institute since the time of its foundation. Fluxes for welding different-purpose steels, low-toxic and high-efficient electrodes, flux-cored wires for welding in shielding gases and without any auxiliary shielding of the arc zone (self-shielding flux-cored wires) were developed. The largest in the world industrial production of different-purpose welding consumables was organized. Characteristics of these consumables are described in numerous catalogues and handbooks. The generalized information about them is given in works [49, 121, 165–168].

Trends of future investigations. In the first decade of the XXI century, steel will remain the main structural material. Rapidly, the new types of high-strength low-alloy steels, including those with an ultra-low content of carbon, heat-resistant steels, steels for structures, operating at low climatic temperatures, steels for cryogenic engineering and different-purpose high-alloy steels will be developed.

The arc welding will occupy, as before, the most important position among the numerous methods of fusion welding. To create the new welding consumables, it is necessary to optimize the systems of weld metal alloying, to search for ways of reducing the content of hydrogen, nitrogen and other hazardous impurities in weld metal to prevent the formation of cracks of different types. The welding-technological properties of materials will be updated to decrease porosity, to prevent crystalline cracks, to improve penetration, weld shapes, removal of slag crust, to increase the arc burning stability, to reduce spattering and evolution of welding aerosols.

Physical and mathematic modeling of metallurgical processes of arc welding will find the further development. The computerized databanks and banks of knowledge, expert systems on different-purpose welding consumables will be created.

A special attention should be paid to updating of equipment and technology of manufacture of welding consumables, to searching for raw materials of a stable quality, to automation of analytic monitoring and in-process control in the manufacturing.

To fulfill all these tasks, the highly-skilled specialists-metallurgists, possessing thorough knowledge in theory of welding processes, physics, chemistry, as well as specialists in the field of information technologies are required. The solution of these problems will promote the progress in manufacture of welded structures and development of welding consumables of the new generation.

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INTERMETALLICS BASED ON TITANIUM AND NICKEL FOR ADVANCED ENGINEERING PRODUCTS

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The most important task of modern materials science is development of advanced light high-temperature materials. Modern high-temperature materials based on solid-solution and dispersion strengthening of the metal matrix, cannot fully meet the requirements made by designers of advanced aerospace products. This task can be solved using advanced high-temperature materials based on intermetallics. The most attractive for these purposes are intermetallics formed by transition metals and aluminium, more often called aluminides. US achievements in this field are noted.

Keywords: *high-temperature alloys, intermetallics, aviation GTE, power equipment, composite materials, blades, flame tubes, single-crystal structure, joint*

Titanium aluminides. The problem of increasing the temperature range of titanium alloy application in gas turbine engines (components, low- (LPCh) and high-pressure (HPCh) chambers, etc.) remains to be urgent. Its solution will allow a marked increase of the power-to-weight ratio of the engine, which is a priority in development of new generation engines.

At present both our company and the leading foreign aircraft manufacturers have developed high-temperature titanium alloys, which reliably ensure long-term operation of parts at up to 550 °C and short-term operation («overshooting») up to 600 °C.

Until recently the efforts of most of the researchers were aimed at development of alloys based on Ti_3Al («α-2»-phase) and TiAl (γ-phase), as these were exactly the materials which could provide the most significant advantage both in terms of power-to-weight ratio and widening the temperature range right up to 800 °C.

However, the problem of improvement of room temperature ductility of these alloys still has not been solved completely. Therefore, despite the considerable scope of research and the emerging new approaches to application and design of parts from titanium aluminides, allowing application of alloys with the current level of properties, these materials have practically not been accepted by industry so far.

At some time VIAM was a pioneer in the field of studying the possibility of developing structural materials based on titanium aluminides. Extensive research was performed of the influence of various alloying elements on the properties of aluminides of different composition, parameters of the technology of shaped casting and strain working were established, technology of modifying the aluminides during their melting was optimized, etc.

So far, the following titanium aluminide alloys are known: Ti_3Al («α-2» phase in the USA — «α-2» superalloys, VTI-2 alloy in RF); Ti_2AlNb («ortho»-phase) «ortho»-alloys, «22-23» alloy (USA), VTI-4 (RF) and TiAl (γ-phase, «46-1-1», USA), VTI-3 (RF), which feature an increased specific high-temperature resistance, fatigue and oxidation resistance compared to titanium alloys.

The achieved level of mechanical properties of intermetallic alloys based on Ti_3Al (super «α-2»-alloys), Ti_2AlNb («ortho»-alloys) and TiAl (γ-alloys) phases is presented in [1]. Analysis of the obtained mechanical properties showed that the modern super «α-2» and γ-alloys cannot meet the designers' requirements — they remain low and no improvement is anticipated in the future. Therefore, the main efforts were focused on development of alloys based on «ortho-phase» [2]. The main advantages of these alloys are as follows:

- high strength and ductility properties;
- low thermal expansion coefficient;
- high low- and high-cycle fatigue values;
- better high-temperature properties at temperatures of 500–650 °C;
- good heat resistance up to temperatures of 700 °C.

The base of «ortho»-alloys is Ti_2AlNb intermetallic (Ti–25Al–25Nb, at.%) with an ordered orthorhombic lattice. The temperature of long-range order breaking up is approximately 900–925 °C, depending on the composition, and no disappearance of the near-range order is observed up to temperatures of 1600 °C [3].

«Ortho»-phase is stable up to the temperature of approximately 625 °C, above which its structure develops an ordered «B2»-phase with fcc lattice. Figure 1 gives the positions of the areas of existence of «ortho», «B2» and «α-2»-phases.

Having a higher melting temperature, low thermal expansion coefficient, higher low-temperature strength and ductility, the «ortho»-phase at temperatures of 650–750 °C has a lower tempo of decrease of the modulus of elasticity, which is indicative of its potential high-temperature properties.

In development of «ortho-alloys», high-melting elements such as molybdenum, vanadium, titanium, tungsten and zirconium are used as alloying elements. Selection of the above elements is due to the fact that they increase the elastic and strength properties of ternary Ti–Al–Nb alloys, lower the oxidability, allow forming optimum structure types improving the duc-

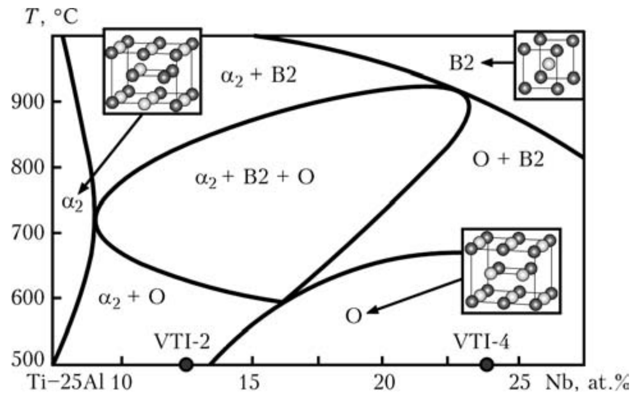

Figure 1. Phase composition of alloys based on Ti_3Al («α-2») and Ti_2AlNb («ortho») phases

tility and reliability characteristics, as a result of the change of the phase composition and structural transformations. In order to improve the high-temperature properties silicon and carbon are added to the alloys, which through formation of complex silicides and carbides increase the temperature characteristics — the short- and long-term strength of the compositions.

So far, several alloys of this type are known, namely VTI-4 (RF), Ti-22-23 (USA), Ti-22-20-3 (China), Ti-22-20-2 (Japan), and Ti-22-25-2-0.5 (France). The alloy base is Ti-(20–23)Al-(20–25)Nb–(1–5) at.% of with other elements such as V + Mo + Zr + Si (VTI-4), Ta (China), W (Japan), Mo + Si (France) [4].

In terms of phase composition, these are two-phase «ortho + B/B2» or three-phase «ortho + B/B2 + «α-2» traces alloys. Depending on the heat treatment modes, the alloys may contain up to 65–85 vol.% of the «ortho»-phase, providing the high-temperature resistance, and 15–35 vol.% of ductile B/B2-phase, which improves the strength, ductility and technological properties of the alloys.

Unlike the traditional titanium alloys, the currently developed «ortho»-alloys have sufficiently high strength (σ_t^{20} > 1100 MPa), relatively good ductility (δ^{20} > 5 %) and high-temperature resistance (σ_{100}^{650} > > 350 MPa), have an increased heat resistance (up to 700 °C). Thus, «ortho»-alloys can quite readily replace high-temperature steels and nickel alloys, used in HPCh rotor and stator with a significant gain in the weight of components and parts (specific weight of «ortho»-alloy is 5.1 g/cm^3, and that of the used nickel alloys is 7.5–8.0 g/cm^3). Moreover, the additional weight gain can be achieved also as a result of replacement of the material of HPCh section stator parts by traditional titanium alloys, which are currently made of steel from fire safety considerations.

However, despite the advantages of these alloys, none of the «ortho»-alloys has been used abroad up to now. This is, apparently, related to the fact that such alloys turned out to be quite complex in the metallurgical production. The need for application of more expensive elements such as niobium, tantalum and tungsten for alloying at their increased content in the alloys, provision of a high uniformity of the ingot composition, application of the rolling and thermal equipment with a protective atmosphere (vacuum or inert gas), strict control of macro- and microstructure in the semi-finished products — are the main causes for slowing down the acceptance of this alloy class by industry [5].

None the less, real prerequisites and technical capabilities are in place to overcome many of the above difficulties. This is achieved by development of sparsely-alloyed «ortho»-alloys and use of the technology of manufacturing titanium alloys, which allow preservation of good adaptability-to-fabrication while retaining an acceptable high-temperature resistance of such alloys, due to solid solution, dispersion and structural strengthening of the ordered «ortho»-phase.

Use of additional alloying, hot working and heat treatment operations allows changing the semi-finished product structure and essentially increasing the high-temperature properties, while somewhat lowering the ductility characteristics, thus ensuring an increase of the operating temperature to 700 °C for advanced «ortho»-alloys. VIAM developed for VTI-4 alloy the technological documentation for pilot production of ingots, slabs, semi-finished sheets (strip and foil), providing the guaranteed level of mechanical properties in the final semi-finished products, and optimized the technology of producing compact multilayer blanks.

Calculation and development results available now show that only the composite materials (CM) — ductile intermetallic matrix + high-strength inorganic fibres — have the potential capability of meeting most of the requirements made of advanced heavy-duty engine and aircracft structures [3–8]. At present, the main obstacle to manufacturing CM with an intermetallic matrix is the mismatch between the thermal expansion coefficients (TEC) of the matrix and fibre, this causing formation of residual tensile stresses and zone of chemical interaction between them. To solve the problem of matching the TEC and chemical compatibility of CM components, investigations are conducted to develop functional coatings for fibres, smoothing the above differences in TEC and minimizing the interaction zone.

Over the recent years, there has been an increasing number of works devoted to searching for intermetallic matrices compatible with the fibres, studying the reaction zone structure and influence of different parameters of CM manufacturing on it, their operational stability, which will allow ensuring high performance of such a material. An example of such an approach can be development in the USA of a CM with an intermetallic matrix based on «ortho»-alloy (22-23 grade alloy), strengthened by high-modulus fibre based on β-SiC silicon carbide (35 vol.%).

VIAM developed the technology of making CM model samples (matrix — VTI-4 alloy + B/B4C fibres), which allowed producing a monolithic CM with complete flowing of the matrix into the inter-fibre spaces and absence of discontinuities and pockets on the interphase of the adjacent layers of the strip. Zone of reaction interaction between the fibre and matrix did not exceed 0.5 μm. This technology was not tried out with silicon carbide fibres, because of the absence of sound fibre material.

Figure 2 gives the areas of application of the developed alloys based on titanium aluminides.

A new direction in development of γ-alloys is investigation of compositions with an increased content of high-melting elements and presence of boron, carbon and silicon. These multiphase cast materials are TiAl intermetallic and high-alloyed β-phase, strengthened by carbides, silicides and borides. It is anticipated that test compositions of such alloys will have σ_c^{20} = = 1000 MPa, ε_c^{20} = 15 % and σ_c^{1000}/γ = = 100 MPa/kg/m^3. Practical utilization of such materials will depend on solution of the issues of improvement of low-temperature characteristics of reliability and lowering oxidability at working temperatures.

Complex chemical compounds — titanium carbosilicides — Ti_3SiC_2 and Ti_3Al–Si–C/B, additionally alloyed by high-melting elements, are particularly attractive as high-temperature materials. Such compositions are cast eutectic alloys, which by their properties are close to ceramic materials. These alloys feature a high specific high-temperature and heat resistance, and it is intended to use them at temperatures up to 900 °C. This work, however, is at the initial research stage, as the issues of interrelation of structure–properties–reliability of such compositions, as well as the technology of part manufacturing (in particular, HPCh and LPT) are still unsolved.

As the high-temperature titanium aluminides (particularly, «α-2» and γ-alloys) have low technological properties, the need for development of a new technology for their processing is becoming obvious. Analysis showed that the most attractive technological sequence is as follows: steel melting out in an induction unit with a copper sectioned crucible, casting shaped blanks for the manufactured parts, and finish stamping of shaped blanks under the conditions of isothermal deformation to final dimensions.

Titanium aluminides based on «α-2»-, «ortho»- and γ-alloys can be widely used in vehicle construction (engine- and motor-car construction). The R&D results available at our Institute allow establishing an efficient manufacturing of valves and impellers of turbocharging units in diesel and piston engines, thus providing a high reliability and corrosion resistance of structures. γ-alloys can also become accepted in such industries as gas- and petroleum-processing units, chemical engineering apparatuses, as well as nuclear engineering, where the requirements to high-temperature materials are less stringent, and specific characteristics, namely high corrosion resistance and resistance to radiation-induced swelling, are required [4, 5, 8–10].

Nickel aluminides. At present the parts and assemblies of GTE hot section (HPT and LPT nozzle and rotor blades, flame tubes, jet nozzle doors, etc.)

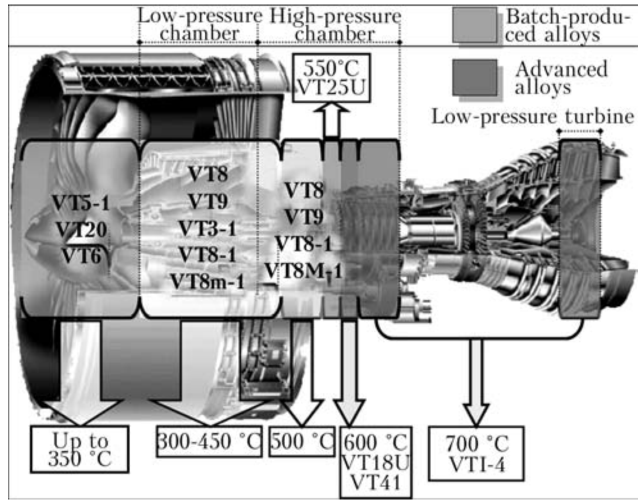

Figure 2. High-temperature titanium alloys in gas turbine engines

are made of nickel/cobalt based high-temperature alloys strengthened by Ni_3Al intermetallic phase (γ′-phase), carbides and borides. Increase of gas working temperatures ahead of the turbine and extension of service life of hot section parts requires increasing in the alloy composition the quantity of high-melting elements, such as tungsten, molybdenum, tantalum, rhenium, etc., thus increasing their density and cost. This stimulates searching for new principles of development of high-temperature materials of a lower density with cost-effective composition, capable of long-term operation in oxidizing media at temperatures of 1100–1300 °C.

Unlike high-temperature nickel superalloys, Ni_3Al and NiAl intermetallics feature a lower density (7.3 and 5.9 g/cm^3, respectively), high modulus of elasticity, oxidation resistance, thus making them attractive for application as matrix material.

Constitutional diagram of nickel–aluminium system is given in Figure 3.

Ni_3Al and NiAl intermetallics have an ordered crystalline lattice, which gives them an increased structural stability, because of a pronounced inhibition of diffusion-controlled processes. High thermal stability of these compounds provides an increase of their high-temperature resistance at a lower content of high-melting elements.

Investigations in the field of development of alloys based on nickel aluminide both in our country and abroad started in the middle of 1980s. So, for instance, five Ni_3Al-based alloys (IC-438 type) were developed and patented in the USA for nozzle blades of ground-based GTE, heat shields of metallurgical furnaces, roller conveyors for firing ceramic ware and other components and parts for various purposes [11–16]. The main disadvantage of foreign alloys is the fact that in terms of high-temperature resistance parameters they are inferior to nickel-base alloys, and, in addition, they have not been tried out in large load-carrying GTE structures.

The main purpose of VIAM investigations performed together with a number of RAS institutes was establishing the main factors, influencing the high-

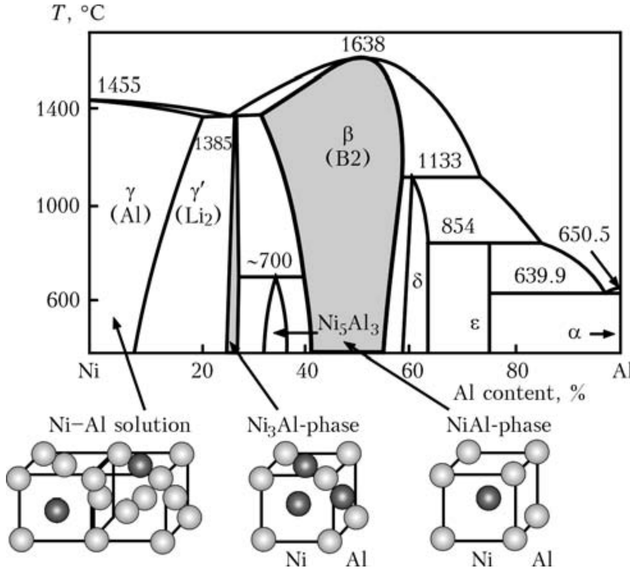

Figure 3. Constitutional diagram of Ni–Al system

temperature resistance of Ni_3Al and NiAl intermetallics and development of structural materials on their basis, not inferior to commercial nickel alloys as to the level of high-temperature resistance, and differing from them by a lower density, cost-effective composition and performance under the conditions of aircraft GTE at up to 1200–1300 °C temperatures in an aggressive oxidizing medium.

At present the most urgent problem is development of structural materials for GTE hot section stator parts — nozzle blades and combustion chamber parts, which are the most massive parts of aircraft engines.

Investigations in the field of technology of manufacturing intermetallic alloys based on Ni_3Al compound allowed revealing two factors affecting the stability of their properties and high-temperature resistance: first, increased amount of gas and other impurities concentrating on grain boundaries; secondly, reduction of casting porosity.

Investigations conducted at VIAM allowed development of the technology of melting out doped alloys based on Ni_3Al and NiAl intermetallics with a minimum content of sulphur, oxygen and nitrogen, providing a high chemical affinity of the ingots. In order to reduce porosity in cast semi-finished products and parts, a technology of high-gradient crystallization was developed and special equipment was designed, which allows reducing casting porosity from 0.2 to 0.02–0.05 %.

To develop high-temperature alloys based on Ni_3Al intermetallic, the influence of chemical and phase composition on high-temperature resistance of Ni_3Al intermetallic was studied at the temperature of 1200 °C, and technology of producing semi-finished products (rods) was optimized to study the high-temperature properties and reveal the advantages over batch-produced nickel alloys.

It is established that optimum properties at the temperature of 1200 °C at testing in the air environment are found in Ni_3Al intermetallic, in which part of nickel atoms is replaced by chromium or cobalt, and part of aluminium atoms is replaced by chromium, titanium, tungsten and molybdenum.

It was shown that single-phase alloys do not have high-temperature resistance properties at the temperature of 1200 °C, as they fail in the brittle mode during long-term strength testing. Increase of high-temperature resistance of Ni_3Al intermetallic in the system of Ni–Al–Cr–W–Ti–Mo alloys at the temperature of 1200 °C is achieved at optimization of the phase composition.

High high-temperature resistance at the temperature of 1200 °C was observed in the alloy preserving a small amount of γ- and β-phases in the intermetallic matrix (nickel- and NiAl-based solid solutions). At the same composition the highest high-temperature resistance at the temperature of 1100 °C is found for cast alloys with a single-crystal structure. Alloys produced by deformation and subsequent recrystallization annealing, turned out to be less high-temperature resistant.

Microstructure of Ni_3Al-based solid solution and alloy on its base with (γ + γ′)-phase interlayers is given in Figure 4. Presence of a small amount of ductile γ-phase in the grain bulk and precipitation of strengthening phases along grain boundaries eliminates material embrittlement along the boundaries and, consequently, increases the high-temperature resistance.

The revealed factors linking the technology of manufacturing and chemical and phase composition

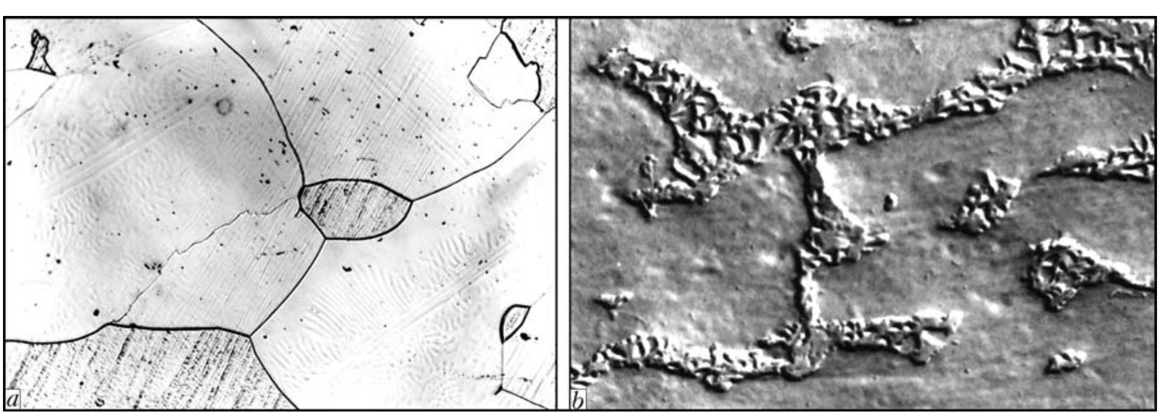

Figure 4. Microstructure of Ni_3Al based alloy in Ni–A–Cr–Mo–W system: *a* — Ni_3Al based solid solution (×250); *b* — sections with (γ + γ′)-phase precipitates along the solid solution boundaries (×10000)

Mechanical properties of cast alloys based on Ni_3Al intermetallics

Alloy grade, certificate	Casting structure	Density, kg/m^3	Mechanical properties at T, °C							
			20			900		1100		1200
			σ_t, MPa	δ, %	σ_{-1}, MPa, at $2\cdot10^7$ cycles	σ_{100}, MPa	σ_{-1}, MPa, at $2\cdot10^7$ cycles	σ_{100}, MPa	σ_{-1}, MPa, at $2\cdot10^7$ cycles	σ_{100}, MPa
VKNA-4, № 1484	Polycrystalline	7840	720	11.5	150	230	250	55	100	23
VKNA-1V, № 1649	Columnar dendritic	7938	740	50	130	250	240	65	120	43
VKNA-4U, № 1598	Same	7910	770	30	230	280	310	95	150	45
VKNA-25, № 1775	Single crystal <111>	8104	1120	10	240	420	370	130	–	48

of Ni_3Al-based compounds, allowed development, certification and conducting industrial trials of structural cast high-temperature alloys of VKNA grade (which stands for VIAM, structural, nickel-aluminium) for hot section parts of batch-produced and advanced GTE with working temperatures up to 1200–1250 °C.

The Table gives the main properties of certified materials at temperatures of 20, 900, 1100 and 1200 °C and their optimum structure in the castings. It is noted that these intermetallic alloys have a good adaptability to fabrication in part production by investment casting method, and are not inferior to the batch-produced nickel alloy JS6U as to their properties.

Trying out these alloys under production conditions in a number of enterprises to manufacture solid-cast nozzle diaphragms of small-sized GTE demonstrated the possibility for lowering the labour consumption of their manufacturing.

Cast single-crystal alloy of VKNA-25 grade is the highest temperature-resistant material based on Ni_3Al intermetallics.

VKNA-25 alloy has good casting properties, thus allowing development of the technology of casting small-sized blades with the specified single-crystal structure.

A feature of intermetallic materials is a lower density compared to their nickel analogs. Technological and operating tests of intermetallic materials showed that their application allows lowering the labour and power consumption by 15–20 % in part manufacturing as the intermetallic materials are used in as-cast state without the strengthening heat treatment. Casting of un-cooled parts, instead of the nickel-alloy cooled ones markedly increases the yield and enables the working temperature to be increased from 1050 up to 1100 °C and the service life by 3–4 times.

Manufacturing «blisk» structures from single-crystal and wrought high-temperature alloys is possible only when applying technologies providing high-temperature resistance of joints of dissimilar nickel alloys. As the cast high-temperature- and super high-temperature-resistant disc nickel alloys are unweld-

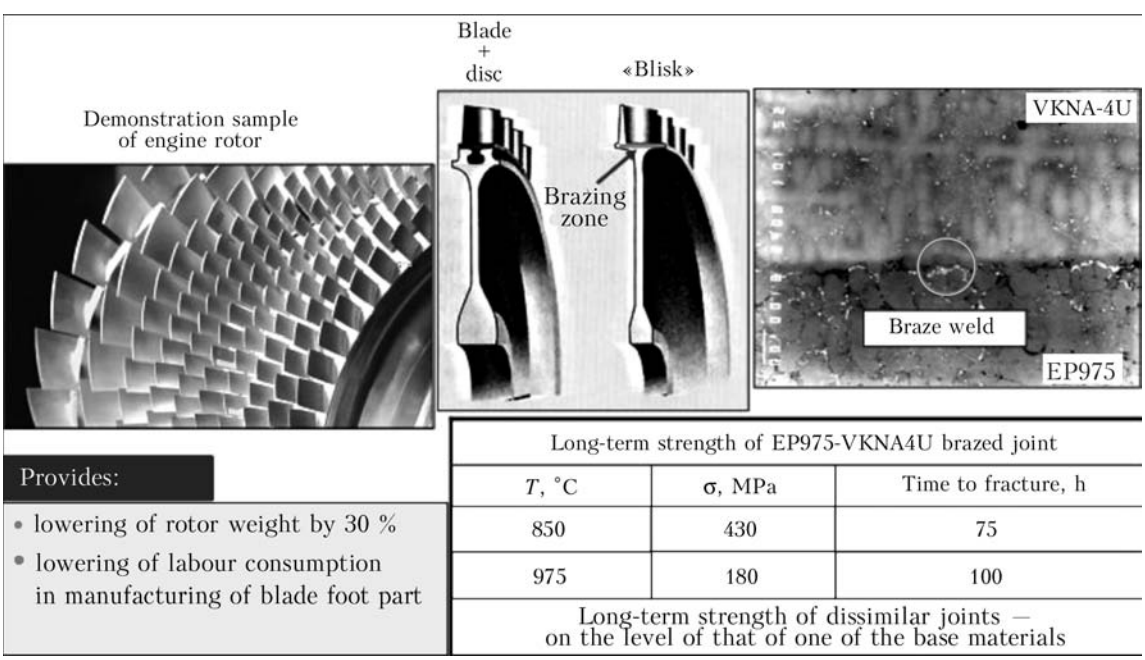

Figure 5. High-temperature brazing of HPT/LPT parts for manufacturing «blisk» type structures

able, because of their susceptibility to solidification and thermal cracks, brazing with nickel-base alloys is an almost sole possibility of producing joints with a high high-temperature resistance comparable with that of the base material (Figure 5).

For a dissimilar combination of materials, it is essential to provide the compatibility of base material heat treatment modes with each other and with the brazing mode, so as to ensure the specified structure and certificate characteristics of each of the materials being joined, respectively.

It should be noted that the structures of the joined dissimilar nickel alloys differ from each other. Producing seam structures closer to those of the materials being joined is determined by the following indices: absence of eutectic structures in the seam middle containing interlayers and sequences of structural components — borides, silicides, intermetallics; close morphology of precipitates of strengthening γ'-phase both in the seam and in one of the materials being joined. In the case of joining single crystals the seam will be detectable as the grain boundary between the single crystal and the wrought alloy.

In conclusion it should be noted that analysis of the local and foreign developments on intermetallic alloys based on titanium and nickel aluminides showed that they are promising high temperature-resistant materials both in the monolithic form and in the form of composite materials, both for advanced products for aerospace purposes, and for industries, in which high-temperature materials are used — vehicle construction (engine and motor-car construction). Results available at VIAM allow establishing a sufficiently effective production of a number of parts, thus providing a high reliability and corrosion resistance of structures.

Application of intermetallic alloys on titanium and nickel base allows a considerable improvement of performance of modern engines and structural elements of flying vehicles, lowering their weight by 20—30 %, cost of parts and components by 25—30 %, while increasing their service life 1.5—3 times.

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ADVANCED JOINING TECHNOLOGIES OF ADVANCED AERONAUTICAL MATERIALS IN CHINA

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A number of modern technologies of joining of hard-to-welding ability materials is presented which are applied in aerospace industry of China. The examples of their practical application are given.

Keywords: *aeronautical materials, joining technology*

Joining technology is key technology for the application of new materials. In this work, some typical research results and progress, especially those obtained in the past 8 years, are presented for the advanced joining technologies of advanced aeronautical materials in China.

Brazing and TLP diffusion bonding of single crystal superalloys and directionally solidified Ni_3Al-base superalloys. In order to meet the needs of high performance aeroengine turbine blades and vanes, brazing and transient liquid phase (TLP) diffusion bonding technologies for single crystal superalloys and directionally solidified Ni_3Al-base superalloys have been investigated in detail in Beijing Institute of Aeronautical Materials (BIAM), China. Some brazing filler metals and interlayer alloys were developed, and sound joints were obtained. The base metals cover the first generation single crystal DD3, the second generation single crystal DD6, and the directionally-solidified Ni_3Al-base superalloys IC6, IC6A and IC10.

For brazing and TLP diffusion bonding of single crystal superalloys, it is necessary to control the bonded pairs with the misorientation less than 10° [1]. For the most interlayer alloys, element B was used as the melting point depressant[1, 2]. DD3 and DD6 were TLP diffusion bonded by using the developed interlayer alloys with the main compositions based on those of the base metals. When the orientations of the bonded pairs were controlled to be matched with each other, the single crystal joint was obtained (Figure 1, *b*). The bonding conditions for DD3 and DD6 were 1250 °C/20 h and 1290 °C/12 h, respectively. Afterwards the joints were heat-treated according to the heat treatment regime of the base metals. For the DD3 joints, the stress-rupture properties of at 980 °C surpassed 90 % of that of the base metal. For the DD6 joints, the stress-rupture properties of at 980 °C were the same as the base metal, and the stress-rupture properties at 1100 °C reach 90 % of that of the base metal (Table 1). Meanwhile, the tensile strength of the DD6 alloy joints at room temperature and 980 °C was at the same level with the base metal. The TLP bonding technology for DD6 alloy has been applied in the manufacture of turbine blades.

For the DD3 alloy joints TLP bonded under 1240 °C/4 h and subsequently heat treated, the tensile strength at 760 and 900 °C was at the same level with the base metal, and the stress-rupture strength at 760 and 1040 °C reached respectively 90 % and 80 % of those of the base metal. The DD3 TLP bonding

Table 1. Stress-rupture properties of TLP bonded single crystal alloy joints

Base metal*	Joint stress-rupture properties			Remarks
	T, °C	Stress, MPa	Life, h	
DD3	980	203	174.35, 157.45, 151.40	–
		226	181.30	
DD6	980	250	129.15, 185.00, 173.50	
	1100	126	112.05, 113.00, 115.45	The stress was raised to 140 MPa after 100 h

Note. For DD3 alloy, σ_{100} at 980 °C = 226 MPa. For DD6 alloy, life under 980 °C/226 MPa ≥ 100 h, life under 1100 °C/140 MPa ≥ ≥ 100 h.

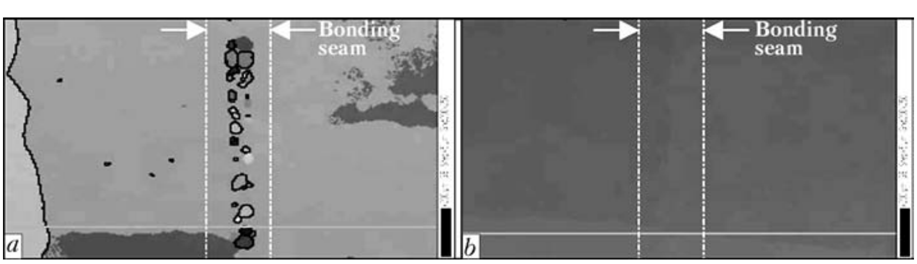

Figure 1. Orientation micro-imagine of TLP bonded DD3 joints: *a* — joint with compounds and grain boundaries; *b* — single crystal joint

Table 2. Stress-rupture properties of the brazed joints of the directionally solidified Ni_3Al-base superalloy

Base metal	Filler metal	Joint stress-rupture properties			Remarks
		T, °C	Stress, MPa	Life, h	
IC10	Co-base	900	160	133.50, 132.25	The stress was raised to 200 MPa after 100 h
		980	80	138.40, 192.25	The same, to 96 MPa after 100 h
	Ni-base	900	160	297.10, 269.05	The same, to 200 MPa after 100 h
		980	80	138.30, 143.05, 128.30	The same, to 96 MPa after 100 h
IC6A	Co-base	900	160	136.25, 110.15, 142.30	–

technology has been put into application for manufacture of turbine blades.

IC6, IC6A, IC10 alloys were brazed with standard Ni-base filler metal and self-developed Co-base filler metals. The typical stress-rupture properties of the brazed joints were listed in Table 2. The brazing technologies have also been applied for the joining of turbine vanes made of IC6 and IC10 alloys.

Sound TLP bonded joints of IC6 and IC10 alloys have been obtained using the interlayer alloys with element B as the melting point depressant. For the IC6 alloy joints, the stress-rupture property at 980 °C was on the same level with the transverse property of the base metal, and that at 1100 °C reached 80 % of the transverse property of the base metal. For the IC10 alloy, the stress-rupture property at 1100 °C reached 90 % of the transverse property of the base metal (Table 3).

Fusion welding of low expansion superalloys. Low expansion superalloys are characterized by high strength, low coefficient of thermal expansion and stable elastic modulus. These features make them to be very applicable for fabricating parts requiring close clearance control in airplane gas turbines. All of them can be welded with tungsten inert gas (TIG) welding and electron beam welding (EBW). However these alloys tend to display some susceptibility to weld cracks [3]. For example, the sensitivity index to weld cracks of alloy GH783 is as high as 29.6 %. But with appropriate pre- and post-weld heat treatment its sensitivity to cracks can be reduced efficiently.

As seen from Figure 2, the GH783 welded joint strength is high, while its ductility is poor relatively. The EBW joint possess strength that matches the base metal. The properties of TIG welded joint can be improved by adjusting the compositions of used filler stick. Welded with filler stick A the joint strength coefficient is 90 % and the ductility is also enhanced.

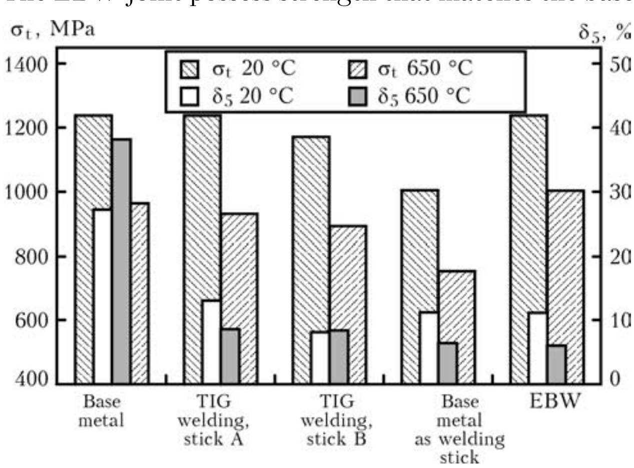

Figure 2. Tensile properties of GH783 welded joints by different processes at room temperature and 650 °C

The welded joint properties can also be improved by using the right combination of pre- and post-weld heat treatments. Studies on alloy GH909 show that pre-weld solution coupled with post-weld ageing can result in better joint properties.

The high temperature stress rupture properties at 650 °C of welded joints achieved both by EBW and by TIG welding for alloy GH783 and GH909 can reach 70 % of the base metal.

Welding of ultra-high strength steels. Investigations were performed on the TIG and EB welded joint properties of two ultra-high strength steels, 16Co14Ni10Cr2MoA and CNG2000. The joint strength coefficient of steel 16Co14Ni10Cr2MoA is 100 %, while the joint ductility and toughness match those of the base metal. The inter-pass temperature has a great influence on the joint impact toughness [4]. It is necessary to keep the inter-pass temperature below 70 °C. Such control will increase the weld cooling and solidifying rate, ensuring finer weld dendrites and thus better impact toughness.

The EB and TIG welded joint strength coefficients of CNG2000 are equivalent to each other and both of them are above 90 %.

Finally the TIG welding technology of 16Co14Ni10Cr2MoA and CNG2000 was respectively applied to the manufacture of the main tail shaft and the shell of flying parameter recorder of one new type of airplane in China.

Table 3. Stress-rupture properties of the TLP bonded joints of the directionally solidified Ni_3Al-base superalloy

Base metal*	Joint stress-rupture properties			Remarks
	T, °C	Stress, MPa	Life, h	
IC6	980	100	62.35, 213.00, 151.40	–
	1100	36	94.00, 89.45, 119.40	–
IC10	1100	36	127.00, 132.00, 104.00	The stress was raised to 40 MPa after 100 h

*Transverse property of IC6 alloy: σ_{100} at 980 °C = 90 MPa, σ_{100} at 1100 °C = 45 MPa. Transverse property of IC10 alloy: σ_{100} at 1100 °C = 40 MPa.

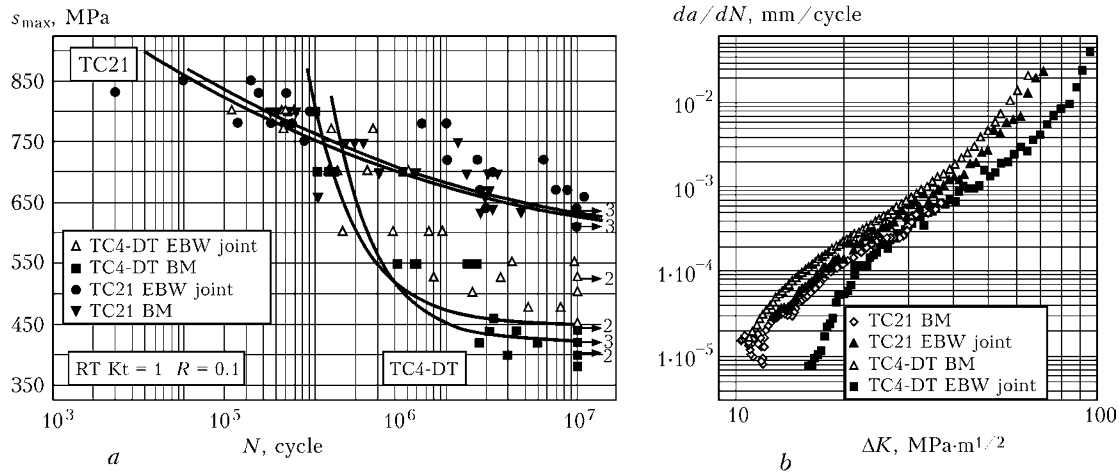

Figure 3. Comparison of the *S–N* fatigue curves (*a*) and fatigue crack propagation rate (*b*) for damage-tolerant titanium alloys and its EB-welded joints

Electron beam welding technology of damage-tolerant titanium alloy. The materials selection criterion of aircraft and engine has changed with the establishment of fail-safe design concept to fulfill the requirement of structural integrity and damage-tolerant design principle [5]. Medium- and high-strength titanium alloys possessing high fracture toughness and low fatigue crack propagation rate have been widely developed all over the world. TC21 and TC4-DT alloys represent commercial titanium alloys in China with the tensile strength of 1100 and 900 MPa respectively, which possess excellent damage tolerance of high fracture toughness and low fatigue crack propagation rate. Both alloys gain the fracture toughness exceeding 90 MPa and low fatigue crack propagation rate (da/dN) up to $9\cdot10^{-6}$ mm/s at $K = 11$ MPa·√m ($R = 0.1$).

TC21 and TC4-DT alloys developed in China possess excellent EB weldability and the joints exhibit outstanding damage-tolerance properties such as high fracture toughness and low fatigue crack propagation. Table 4 lists the EBW joint properties and Figure 3 presents the comparison of the *S–N* fatigue curves and da/dN for damage-tolerant titanium alloys and their EBW joints.

The fatigue property of EBW joints for the alloy TC21 is equal to that of the base metal, whereas, for the alloy TC4-DT, the fatigue life of the EBW joints is even prior to the base metal itself obviously at the mean tensile stresses (less than 520 MPa). The lamellar microstructure of titanium alloys shows more favorable properties of fracture toughness and resistance to fatigue crack propagation than the equiaxed or duplex microstructure [6]. The EBW heat input coarses the prime β-grain size and thicken the α-lamellar, resulting in the improvement of the fracture toughness and the resistance to fatigue crack propagation.

Welding technology of Ti_3Al-based alloy. The effect of EBW heat input on the microstructure and mechanical properties of Ti–24Al–15Nb–1Mo (at.%, named as TD3 alloy, developed in BIAM) joint was investigated on the basis of thermal simulation experimental results. The suitable EBW process parameter windows are then determined to achieve the satisfying joint ductility and fracture toughness. It is shown that the as-welded joint microstructure was composed of prime α_2-phase and β- transformed microstructures including a small amount of retained β/B_2-phases and secondary α_2-, some O-phase and ϖ-phase.

The results show that plastics of base metal and joints can be recovered again by post-weld heat treatment. Compared with the base metal, the joints exhibit equal strength, while the prolongation rate and impact toughness reach 70 % and 60 % of the base alloy respectively (Table 5). It is believed that the formation of O-phase during welding remarkably improves the tensile strength, and the joint shows a satisfactory plastic owing to the order retained β/B_2.

Welding of aluminum-lithium alloys. In China more attention is placed on aluminum-lithium alloy 5A90 and 2195. The main problems associated with them are weld porosity, cracks and the softening of welded joints.

The porosity problem is serious for the 5A90 welding. As indicated by our works the occurrence of porosity can be attributed to the release of gas due to heating of the oxidation film on the material surface

Table 4. Properties of EB-welded joint of TC21 and TC4-DT alloy

Titanium alloy	Specimens tested	σ_t, MPa	$\sigma_{0.2}$, MPa	δ_5, %	ψ, %	a_{k_u}, J/cm^2	K_{IC}, MPa√m	Fatigue strength ($N = 1\cdot10^7$; $R = 0.1$; $f = 120$ Hz)	
								$K_t = 1$	$K_t = 3$
TC4-DT	EBW joint	914	854	13.2	48.6	56.9	91.4	450	–
	Base material	929	878	16.2	49.5	58.0	89.8	421	–
TC21	EBW joint	1138	1051	8.3	20.8	29.8	88.59	643	315
	Base material	1174	1083	11.3	20.0	51.5	90.6	653	277

Table 5. Comparison of mechanical properties of the TD3 alloy EB-welded joint and the base material

Welding parameters	Heat treatment	σ_t, MPa	δ_5, %	ψ, %	Tensile fracture location	a_{k_u}, J/cm^2
v = 14 mm/s, E = 0.56η	Post-weld heat	1044	6.2	13.8	Base material	3.1
	As-welded	1045	3.6	7.7	Near-weld zone	6.0
	Solid solution and aging	1062	8.9	14.3	Same	4.9
TD3 base material	Solid solution	1108	6.3	12.2	–	7.0

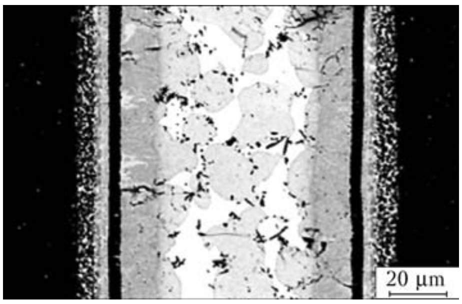

Figure 4. Microstructure of SiC/ SiC joint brazed with newly-developed Co-based brazing foils at 1150 °C for 10 min

[7]. Pore-free welded joints can be produced by pre-weld chemical cleaning, mechanical polishing just before welding and good shielding.

As to alloy 2195, the prominent problem is its high susceptibility to weld cracks. Through selecting appropriate welding parameters, controlling weld shape, optimizing filler compositions and adopting auxiliary measures its crack susceptibility is reduced efficiently and crack-free welded joints can be acquired.

Both the alloys 5A90 and 2195 are subjected to the problem of joint softening. It is of some difficulty for them to obtain welded joints with strength coefficient above 60 %. Special filler metal has been developed for 5A90 by which the weld grains are refined and the joint properties are improved obviously. The properties of welded joints in 2195 are also improved by adjusting the filler metal compositions. In particular, due to the use of auxiliary materials the weld metal grains are refined, the weld formation is improved, and the joint strength is increased markedly. Finally its TIG welded joint coefficient is approaching 70 %.

Brazing of Si_3N_4 and SiC ceramics. The main limitation of brazing for joining ceramics is finding braze compositions that have desirable properties. Au–Ni–V–Mo filler alloy provides a room-temperature four-point bend strength of 393 MPa for Si_3N4/Si_3N_4 joints, the same level strength can be maintained up to 500 °C, and 65 % of the room-temperature strength has been retained at 600 °C [8]. In addition, it has been reported that the highest room-temperature four-point bend strength of the Si_3N_4/Si_3N_4 joints using Ni–20.35Cr–10.04Si (at.%) brazing alloy is 115 MPa, whereas about 210 and 220 MPa have been achieved when the joints are tested at 800 and 900 °C respectively [9]. Recently, the wetting behavior of Ni–V, Co–V and Ni–Cr–V alloys on Si_3N_4 was studied by the sessile drop method [10], and on this basis a V-containing Pd-based braze has been newly developed for Si_3N_4/Si_3N_4 joining, and the corresponding joints exhibit above 200 MPa bending strength not only at room temperature but also at 800 °C.

In terms of SiC brazing, progress has so far been rather slow. It should be noted that the control of interface reactions between the SiC matrix and the brazing alloy is a significant issue and should be considered in the design of new high-temperature brazing alloy for SiC joining. In BIAM, one Co-based brazing alloy, CoFeNi(Si, B)CrTi, was newly developed for SiC/SiC joining [11]. The periodic banded reaction structure that existed at the interface between SiC and traditional Ni-based or Co-based braze has been eliminated by the newly-designed Co-based brazing alloy. The reaction layer of the SiC/SiC joint under the optimum brazing condition was composed of multi-layer silicides and TiC band, and the matrix of the central part of the joint contained Co–Fe–Ni–Cr–Ti–Si phase and Fe–Co–Cr–Ni phase, with scattering dispersion of many small TiC particles. The formation of TiC in the joint contributes not only to the elimination of the periodic banded reaction structure, but also to the high joint strength and the high-temperature stability. The brazed SiC/SiC joints (Figure 4) give the average three-point bend strengths of 142.2, 162.3, 188.2 and 181.5 MPa at room temperature, at 700, 800 and 900 °C respectively.

Summary. The main results and progress of the research on joining technologies of advanced aeronautical materials in the past 8 years in China are presented. The development of high performance aircraft and aeroengine sets an increasing demand on joining technologies of advanced aeronautical materials, and many technique problems still remain to be solved. With the continuous study and progress, more and more research results would be obtained in future, and they will be put into applications.

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LASER TECHNIQUES IN MODERN WELDING TECHNOLOGY. RESEARCH AND APPLICATIONS

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The paper contains a review of laser welding research works conducted at Instytut Spawalnictwa (Poland). It also presents the equipment and investigation related to the use of hybrid processes and describes application of two types of laser groups, i.e. CO_2- and Nd:YAG lasers, in welding processes providing examples on the use of these technologies in machine-building and automotive industries, as well as for welded tailored and tubular blanks.

Keywords: *welded structures, laser methods of joining, types of lasers, hybrid technologies, tailored and tubular blanks*

The intense use of laser technologies remains in close relationship with growing demands aimed at welded structures and industry-dictated quality requirements addressed to welding technologies. Laser technologies are applied in the processing of various types of materials used to produce different grades of structural steels, aluminium alloys, plastics, woven fabrics etc. Among all types of technological lasers used in the aforementioned applications, it is CO_2, YAG, HPDL and, increasingly, fibre lasers that seem to be taking the priority. Very often, the laser is the only available and irreplaceable instrument able to meet technological challenges imposed by the manufacturing of highly advanced industrial products.

Nowadays the development of welding laser technologies is strictly tied to pure basic research, yet it also enforced by the need to develop and implement specific practical applications.

In pure basic research area most attention is focused on welding by means of hybrid methods, welding with a scanning beam (remote welding), welding with a filler metal or on testing weldability of new steel grades and other technologically advanced materials. In case of industrial applications, primary interest connected with laser welding technologies comes from automotive and shipbuilding industries as well as from rail-vehicle production and other manufacturing sectors.

Despite numerous advantages available particularly to firms grouped in SME's segment, the change of manufacturing technique and replacing classical welding technologies with laser welding is often confronted with a number of difficulties. The primary reasons include fear of significant investment commitments and risks related to practical implementation of modern manufacturing techniques.

One of more significant tasks which can be undertaken by research and development establishments is to assist the above-mentioned enterprises in transfer of modern technologies to industrial production and in overcoming certain reservations about new technologies through justification of their applicability as well as to help develop technologies and prepare prototype lots to be used for tests and investigations. Through research and implementation works in the field of laser technologies, Instytut Spawalnictwa aims to accomplish the aforesaid objectives.

This article outlines works and research activities dedicated to production-related laser welding applications conducted at Instytut Spawalnictwa in the last few years.

At present Instytut Spawalnictwa has at its disposal two (Figure 1) modern universal laser stations meeting requirements of many industrial applications.

Research work. *Research on hybrid methods*. Research on hybrid methods was devoted to application and adaptation of standard laser and arc units as well as gas mixtures in welding with hybrid methods. The research works involved aluminium alloys and increased-strength structural steels (EN AW 6101 and EN AW 5754).

Research-related tests incorporated the use of Instytut-owned laser units and standard modern sources applied for MAG/MIG and TIG welding such as, among others, Kemppi Pro Evolution, Fronius and Aristo TIG. In order to conduct the investigation it became necessary to design special mechanical and electrical systems ensuring precise location of both heat sources and allowing device control systems to be connected to laser and arc welding (Figure 2).

In the equipment configurations as those presented above, the hybrid laser + MIG/MAG welding offers a considerable increase in welding efficiency if compared to MAG/MIG method alone (increased rate of welding process) as well as an opportunity to perform butt joints connecting sheets prepared for welding with 1.2 mm gap (Figure 3, *a*). The video recording made it possible to assess how the welding process is affected by MAG/MIG-related various gases and shielding mixtures as well as various gases fed from an additional side nozzle; this being of particular importance in case of hybrid welding with the use of CO_2 laser. Inappropriate selection of shielding gases in the hybrid CO_2 laser + MIG/MAG method may lead to detachment of a plasma cloud entirely blocking laser radiation (Figure 3, *b*). In case of aluminium alloys, hybrid YAG laser + TIG welding can be performed by means of 2 kW YAG laser and f of 200 mm

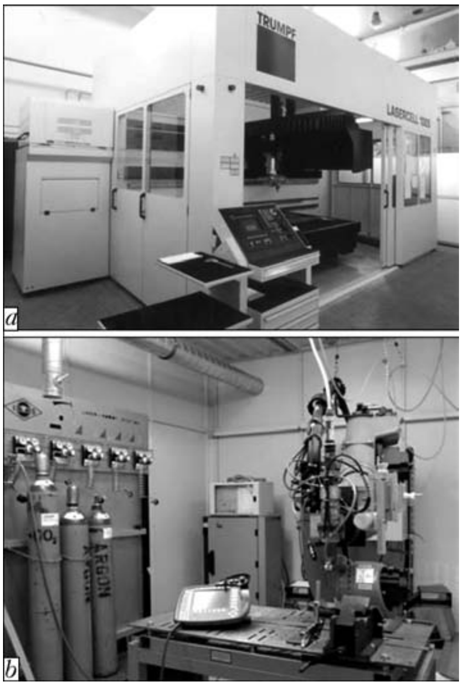

Figure 1. Laser stations at Instytut Spawalnictwa: *a* — lasercell TLC 1005 with CO_2 laser TLF 3800; *b* — YAG laser HL 2006D/LCU with KUKA robot KR30/2 HA and welding head D70

head. The application of the laser + TIG method (Figure 3, *c*) for joining sheets of different thickness allowed obtaining high quality joints and reducing structural notches. The aforementioned technology was used for, among others, welding tailored blanks.

Research on laser welding of tailored blanks and tubular blanks. The concept of making tailored assumes joining (primarily by means of laser welding)

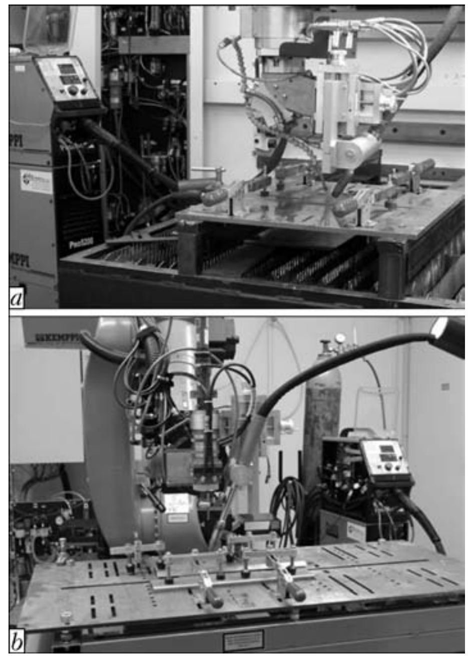

Figure 2. Stations for testing hybrid processes: *a* — test station for hybrid CO_2 laser + TIG/MIG welding (system with lasercell TLC 1005, 3800 W, f = 270 mm and MAG/MIG Kemppi Pro Evolution); *b* — test station for hybrid YAG laser + TIG/MIG welding (system with YAG laser HL 2006D/LCU, 2000 W, f = = 200 mm and MAG/MIG Kemppi Pro Evolution)

various sheets geometrical and physical features of which are selected on the basis of structural and economical analysis of press-formed elements. Such a solution enables the manufacturing of blanks from various grades of steel, from sheets of different thickness and press-formability as well as from sheets with different types of coating. It is also possible to use prop-

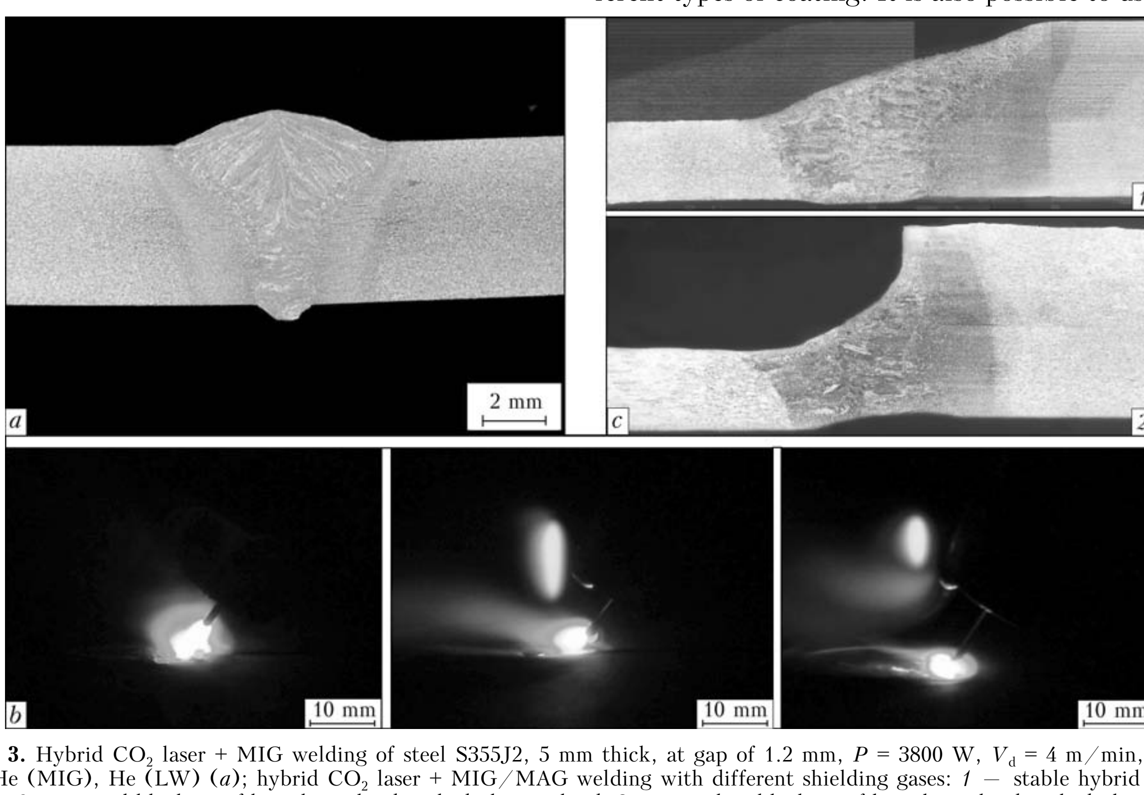

Figure 3. Hybrid CO_2 laser + MIG welding of steel S355J2, 5 mm thick, at gap of 1.2 mm, P = 3800 W, V_d = 4 m/min, in Ar + 50 % He (MIG), He (LW) (*a*); hybrid CO_2 laser + MIG/MAG welding with different shielding gases: *1* — stable hybrid welding process, *2* — partial blocking of laser beam by detached plasma cloud, *3* — complete blocking of laser beam by detached plasma cloud (*b*); hybrid CO_2 laser + TIG welding (*c*) of electrogalvanised steel, 0.7 + 1.5 mm thick, LW P = 2200 W, TIG — 150 A/15 V, in argon (*1*) and LW P = 2200 W, in helium (*2*)

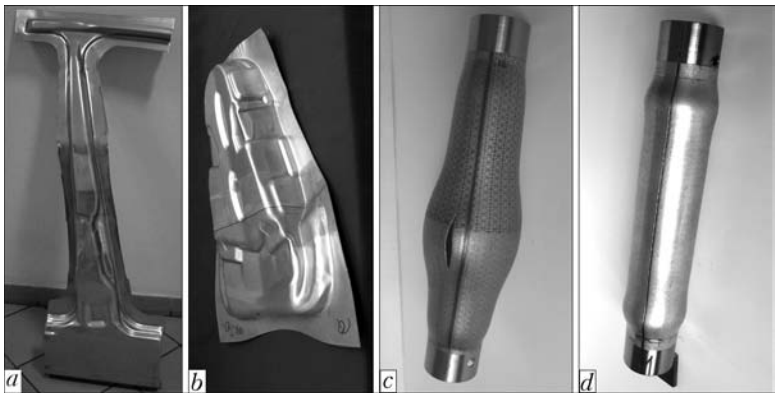

Figure 4. Tailored and tubular blanks welded with laser: material H180LAD, FeE 275 F ZNT/7.5/2s at P = 3800 W in helium (*a, b*); electrogalvanised steel FE 450 DP, H180BD + Z, tube of 1.5/45/300 mm at P = 2000 W in argon (*c, d*)

erly selected strips to prepare blanks of dimensions exceeding the maximum dimension of a sheet as well as preparing blanks with technological openings (Figure 4, *a, b*). Both Instytut Spawalnictwa and the Silesian University of Technology have conducted research on laser welding and press-formability of such blanks.

Modern materials used in hydro-forming of car body elements include also laser-welded tailored blanks and tubular blanks. Internal fluid-based bulging of tubes welded with laser in closed dies enables production of complex-shaped elements used for manufacturing of car body parts responsible for passive safety. The basic obstacles which accompany the welding of such structures are determined by the need to perform precise and high-quality welds entailing the minimum removal of protective coating (zinc) in the joint area as well as by the necessity to obtain joints without excessive structural notches and provided with appropriate strength and plasticity characteristics when confronted with triaxial stress during a press-forming process.

Instytut Spawalnictwa applied YAG laser used for laser welding of tubes made of FE 450 DP (dual phase) steels as well as H180BD + Z steels used in hydroforming (Figure 4, *c, d*).

Industrial applications. *Laser applications in joining precise elements with linear and circular/circumferential welds*. Laser welding makes it possible to perform circular and circumferential welds with a precisely selected fusion depth, small width of face and root as well as small HAZ. The aforementioned method may be used for joining precise elements of rotational symmetry such as disks, rolls, tubes, rings, cylinders etc. It can also be applied in joining elements with precise linear welds (both continuous and section-wise) as well as by means of spot welds.

The requirements concerning properties of welded joints vary and strictly depend on designer's assumptions related to operational specifity of a given element. Major demands may include proper static strength of a joint (often referred to by the user as an appropriate fusion depth or weld thickness), proper fatigue strength or, for instance, the minimum possible strain occurring after a welding process. Such demands may be fulfilled through ensuring proper preparation of joints prior to welding, precise laser beam guidance along designed trajectory and proper selection of welding parameters. Apart from the basic welding parameters such as laser beam power and speed of welding, it is essential to determine and investigate the impact of remaining welding parameters (e.g. laser beam entrance angle, laser beam focus location, change of laser beam power in relation to welding trajectory, geometrical interrelations of the system of laser head–welding clamp of arc welding method in case of hybrid welding) which affect the final outcome of welding process. Selected welding parameters should be always verified with reference to a given joint so that user-specified

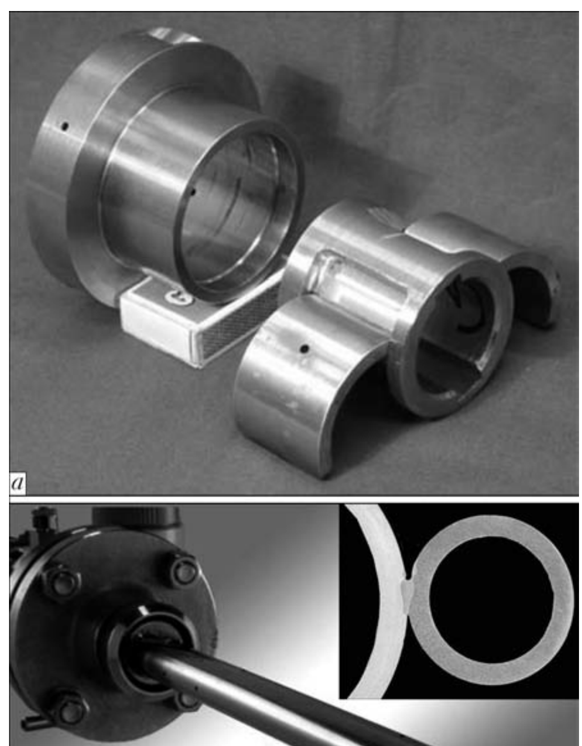

Figure 5. Elements of hydraulic jaws: quench-tempering steel, weld depth of 4 mm, P = 3800 W in helium (*a*); probe for flow measuring system: material X2CrNi18-9, tubes 12/6/1200 + 25/6/1200 mm at P = 1700 W in argon (*b*)

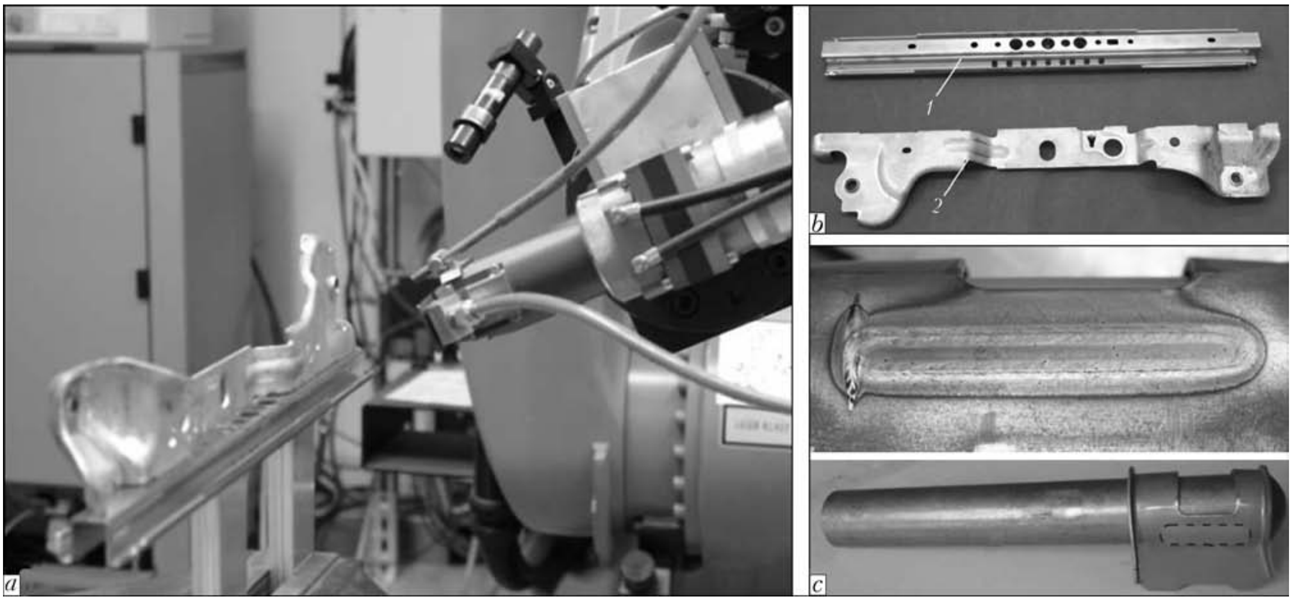

Figure 6. YAG laser welded elements of car seat: material S500MC, 0.8 + 1.5 mm, P = 2000 W in argon (*a, b*); elements of shock absorber: material SAE 1008 + S355MC, tube 50/2 mm, bracket of 2.5 mm, P = 2000 W in argon (*c*)

requirements could be met. Presented below are selected examples of laser welding technology applied during preparation of industrial production elements for which Instytut Spawalnictwa has developed related welding technologies.

Hydraulic jaws of wood processing tools. The design of hydraulic jaws (Figure 5, *a*) incorporates a concentric connection of several sleeves so that between the internal walls of the elements it is possible to form free spaces through which liquid medium can be funnelled under very high pressure. The deformation of internal sleeve of the clamp results in fastening the latter on the machine tool spindle. Laser welding technology enables the preparation of precise and tight circular welds between individual clam components transferring very high pressure.

Elements of media flow measuring system. One of the basic elements of probes (sensors) used for measuring flow of volatile gases and pure liquids in closed pipelines and exhaust systems (large-size channels) is a set of welded pipes (made of X2CrNi18-9 steel) with properly located openings. A continuous weld or a row of section-wise welds should join pipes (Figure 5, *b*) along the contact point of cylinder forming lines without interfusing a wall of any pipe or disturbing its inner diameter. The whole connection should be strong enough for the aforesaid pipes to be installed in a given type of a measurement probe. During the process of welding it is necessary to minimise welding strains as well as retain, as much as possible, rectilinearity of welded pipes. Performing the joints as described above requires very precise location of a laser beam in relation to the contact point of the forming pipes, analysis of stress and strain in the whole structure as well as selection of appropriate sequence of making single- and double-sided welds. The use of YAG laser and appropriate sequence of section-wise enable the fulfilment of the aforementioned requirements.

YAG laser in automotive applications. *Elements of car seat bracket and front suspension telescope*. The element of a car seat bracket consists of two components; element 1 («male» section) is press-formed from H800LA sheet 1.8 mm thick, element 2 (wing) is made of S500MC sheet 2.5 mm thick (Figure 6, *b*). Both elements need to be joined in a manner which allows retaining high strength and very high tolerances of perpendicularity of specific surfaces of both elements. YAG laser welding applied in a robotized station (Figure 6, *a*) as well as maintaining appropriate welding sequence ensures proper joining of elements.

Car shock absorber elements. The design of car shock absorbers imposes the connection of external shock absorber pipe of 50 mm diameter and 2 mm thick wall, made of SAE 1008 steel, with a clamping ring press-formed from S355MC steel (Figure 6, *c*). Laser welding method may replace the so-far MAG welding technology known to cause significant deformation and failing to ensure required joint quality.

Summary. Laser technologies have contributed to introduction of many new, often revolutionary, technical solutions and stimulated innovation in many industries allowing reducing general manufacturing costs. The possibility to use these technologies has shaped a new approach to the design of many subassemblies. Today, thousands of different types of lasers are employed in various industrial sectors. R&D centres of many companies are equipped with state-of-the-art laser systems and spare no effort to expand the to-date laser technology application areas. Instytut Spawalnictwa intends to continue and develop research works in this field supporting the domestic industry in the use of the said technologies.

PROSPECTS OF WELDING RESEARCH DEVELOPMENT IN LATIN AMERICA COUNTRIES ON THE EXAMPLE OF BRAZIL

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In this paper an overview of the research on welding capability and potentiality in Brazil is presented. Through a comparison with steel and shielding gas consumptions the potential for an increasing demand for research on welding is established. The capability and tradition on this matter is discussed. Statistics shows that the investment carried out on research is increasing faster than price inflation and welding product spending. It is described a survey of the number of Brazilian groups research and the main subjects under study, and is presented as an example the activities and infrastructure of one of the Brazilian groups.

Keywords: *welding in Brazil, research centers, trends of activity, statistics, investment climate*

Brazil as a welding producer. One reasonably safe parameter to measure the welding production in a country is the consumption of flat steel. According to a report from the Organization for Economics Co-operation and Development (OECD) 2007, the so-called BRIC economies (Brazil, Russia, India and China) are leading the growth of world demand. Chinese steel consumption reached 318 mln t in the first nine months of the year 2007, up 30.8 mln t or 10.7 % from the same period of the year 2006. Indian consumption is also increasing at a double-digit pace, though from a much lower level of around 45 mln t. In response to growing demand, India may have become a net importer of steel during the course of 2007. Brazilian steel demand is being fuelled by dynamic growth in steel-using industries such as construction, mechanical machinery, and automotive manufacturing (Table 1). In Russia, the booming oil and gas industry and growth in household income continues to stimulate demand for steel. Steel demand in these economies is expected to continue displaying strong growth in 2008, though some moderation will be felt from the global economic slowdown.

A record-setting year for the Brazilian automotive industry and a boom in the civil construction industry stoked demand for steel products are pushing up domestic sales. The two industries represented nearly 60 % of Brazilian steel sales (Fick, 2007). In relation to last year figures, the steel consumption in the automotive industry raised 17.8 %, 16.2 % in the civil construction, 30.7 % in capital goods and reached 40 % in pipes construction (globo.com, 2007). Despite the fact that the figures are well below of some large steel users, such as China, EUA, Japan and Russia, it is believed that Brazil is the 10th in the country rank by steel production, just below Ukraine and Italy (Wikipedia, 2006). Considering that steel production and consumption is moving more and more toward emerging market countries, one can expect a significant increase in the Brazilian welding production in the next years in contrast to in developed countries (accordingly, there is a feeling that there are fewer and fewer places performing welding research in the latter countries).

These initial paragraphs are to show the importance of welding in a country like Brazil (and to some extend in Latin America). These data are reinforced by an estimation of shielding gases consumption in Brazil during the last year. Table 2 was elaborated by compiling information available in industrial reports. This Table shows that the consumption of shielding gas has been increasing at approximately same rate as flat steels. But it is interesting to point out that the price of the product has also been raised along the past years (even if one deduces the increase of annual price inflation, which, according to available data (IDOP, 2008) was of 7.6 % in 2004, 5.7 % in 2005, 3.1 % in 2006 and 4.6 % in 2007. The reason claimed

Table 1. Consumption of flat steel (IBS, 2008)

Year	Consumption, t·10^6	Note
2006	11.1	
2007	13.4 (+20 %)	Preliminary data
2008	14.6 (+9.4 %)	Estimated

Table 2. Shielding gas consumption in the last years in Brazil

Year	Consumption, mln m^3	Δ, %	Price, USD/m^3	Δ, %
2004	56	–	2.23	–
2005	60	+7	2.60	+17
2006	69	+15	2.90	+12
2007	78	+13	3.14	+8

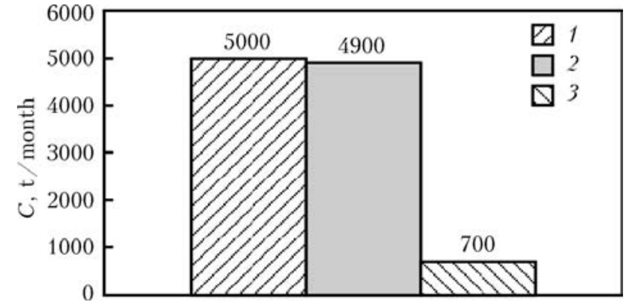

Figure 1. Consumption *C* of welding consumables in Brazil in 2007 by the main processes: *1* — MIG/MAG; *2* — coated electrode; *3* — flux-cored wire

by the manufacturers is the lack of installed production capacity in relation to the demand, but this should be regularized in the next two years with new investments on new plants. However, even though the demand for shielding gases is increasing, around 46 % of the welding consumption in Brazil is made with coated electrode, as seen in Figure 1. Brazil still has room for modernizing its welding manufacturing means.

It is well known that the economic policy at the moment is for strengthening the internal market and for swapping progressively primary and semi-manufactured goods exportations by more aggregate value goods.

Thus, research, development and innovation must be the tone for the country if the government wants to maintain the consumption goods competitive in the global market. Lack of innovation is not only a matter of low competitively but, rather, a sign to stagnation. However, research leading to industrial application is a reasonably new approach in Brazil. Mota (1999) in an article on university and industry interactions cites

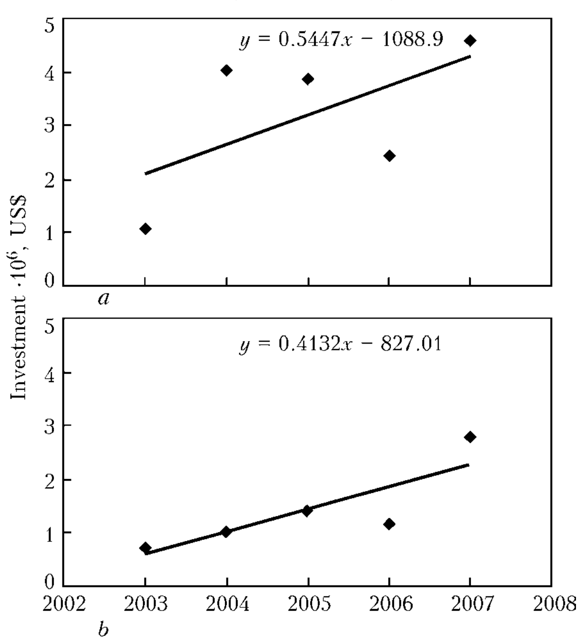

Figure 2. Annual investments in research projects: *a* — by CNPq (2007) in spending and equipments, not including personnel, related to metallurgy, mechanical, airspace and naval engineering (only projects freely proposed by researchers, excluding the government oriented projects; *b* — by Fapemig (2007) in spending and equipments, not including personnel, related to all engineering fields (only projects freely proposed by researchers, excluding the government oriented projects)

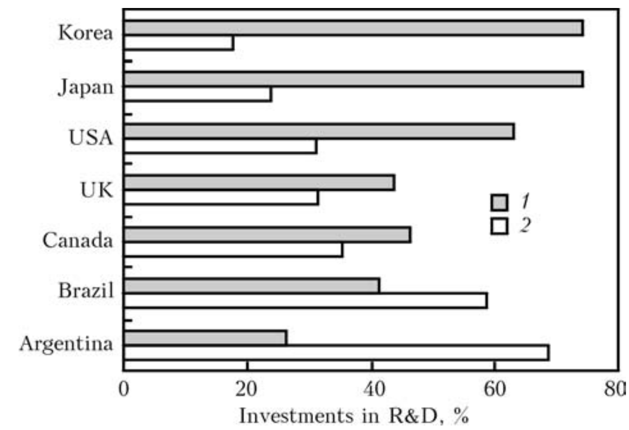

Figure 3. Relationship between investments made by industries and government: *1* — industries; *2* — government

out that, amongst the main problems faced to Latin American countries is the fragile mechanism of industrial culture formation. It is based on the purchase of «technological packets» without a posterior process of assimilation and adaptation of the imported technologies, in special when these technologies are demanded by monopoly and multinational companies.

But this profile has been changing in the last 10 years, with the creation of dedicated governmental funds to boost researching. Figure 2, *a* presents a tendency of augmenting the values invested in research projects by the main federal government organism for research development (CNPq), while Figure 2, *b* shows similar data for a state agency (Fapemig — State of Minas Gerais). One can observe a jump of more than 100 % of investment in the last 4 years carried out by CNPq (considering an average linear increasing tendency) and of around 260 % in the same period carried out by Fapemig. These figures are well above the average increase of the Brazilian Gross Domestic Product (GDP), which was bellow 5 % per year. There is no similar data for welding projects, but one can consider that welding is a fraction of the investments on the engineering fields used to compile data that led to those figures.

Brazilian research groups. Coherently with a short tradition of the industries in putting in effort on research inside Brazil, there is not a national re-

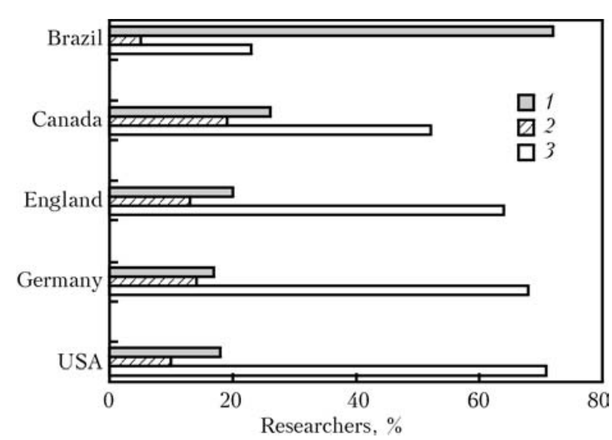

Figure 4. Relationship amongst researchers working for industries, government and universities (Elias, 2006): *1* — universities; *2* — government; *3* — industries

Figure 5. Distribution of sites by region, in which welding technology is to some extent researched in Brazil

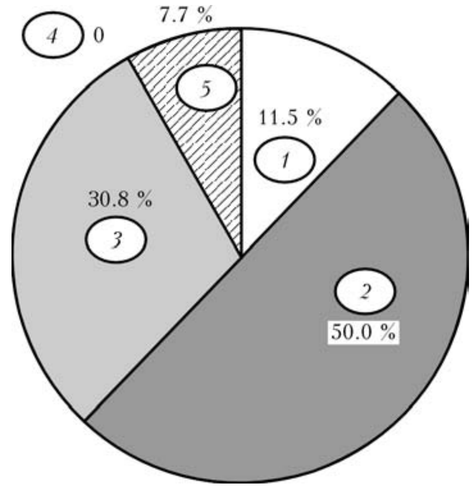

Figure 6. Distribution of welding groups by emphasis on the study interests: *1* — essentially metallurgy; *2* — with priority on metallurgy (process is a tool); *3* — with priority on processes (metallurgy is a tool); *4* — covers essentially processes; *5* — dedicated to simulations, residual stresses and structure integrity

search center in Brazil dedicated to welding, such as Paton Institute, ISQ, TWI, EWI, etc. There are some researching and technological centers gathering different areas, but none of them, so far, have expertise on welding technology. In Brazil, on the contrary of the more industrialized countries, more than 50 % of expenditure in R&D is carried out by the public sector (Figure 3). The researcher number ratio universities/(researching centers and industries) presented a status even further from what happens with the more developed countries (Figure 4). Thus, the role of university research as complementary to, and not substitute for, industrial research is emphasized.

Thus, a survey was carried by the author of this article to delineate what is on concerning welding research in Brazil. For the reason shown above, the target was the universities and alike. After sorting paper authors in the welding related Brazilian conferences and searching in a database of Brazilian researchers, managed by CNPq, it was identified 35 sites that somehow work (not necessarily developing research at high level) with welding technology. 26 out of 35 were universities, 7 technological colleges and 2 researching centers. The distribution of these sites in Brazil (Figure 5) shows a concentration in the southeast region (the most industrialized), but a significant amount of sites are located in the northeast of Brazil, not very industrialized area, in contrast to the south area (the second more industrialized area).

Once identified the targets, a questionnaire was sent to the researchers connected to those sites. 91 % of the welding groups related to the sites sent back the answers, but only 68 % of the groups declared to have welding as the main subject. Thus, by extrapolation, 24 groups inside universities and technical colleges devote time to study welding in Brazil (an estimate is that about 6 out of these groups has already reached experience and lab conditions to develop welding at the level needed to help Brazilian industry to be competitive). This figure is probably low for the Brazilian needs (according to the International Comparison Program (ICP) of the the World Bank — Fix and Tuck, 2008, Brazil accounts for one-half of

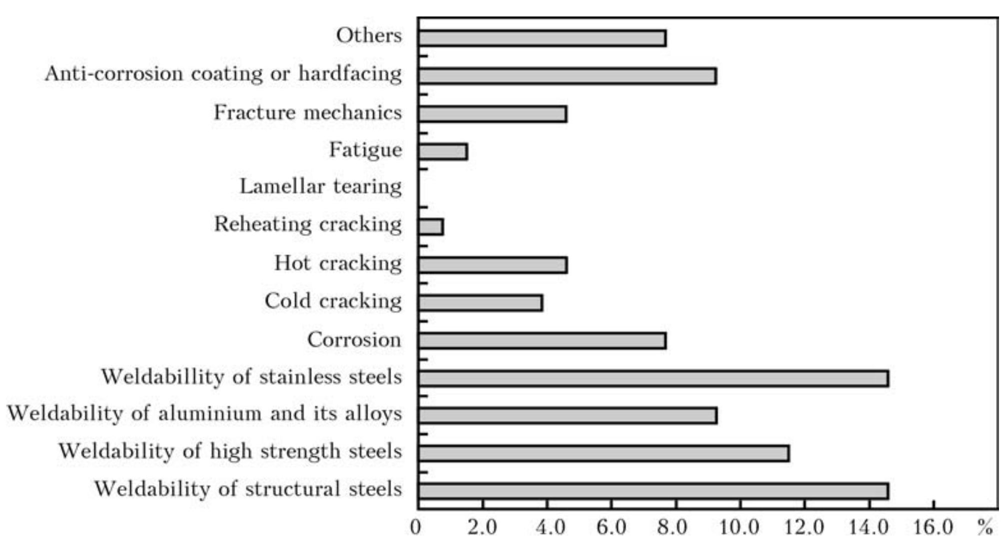

Figure 7. Main aspects on metallurgy studied by the groups in Brazil (responses from only groups that claim to working on welding as first subject)

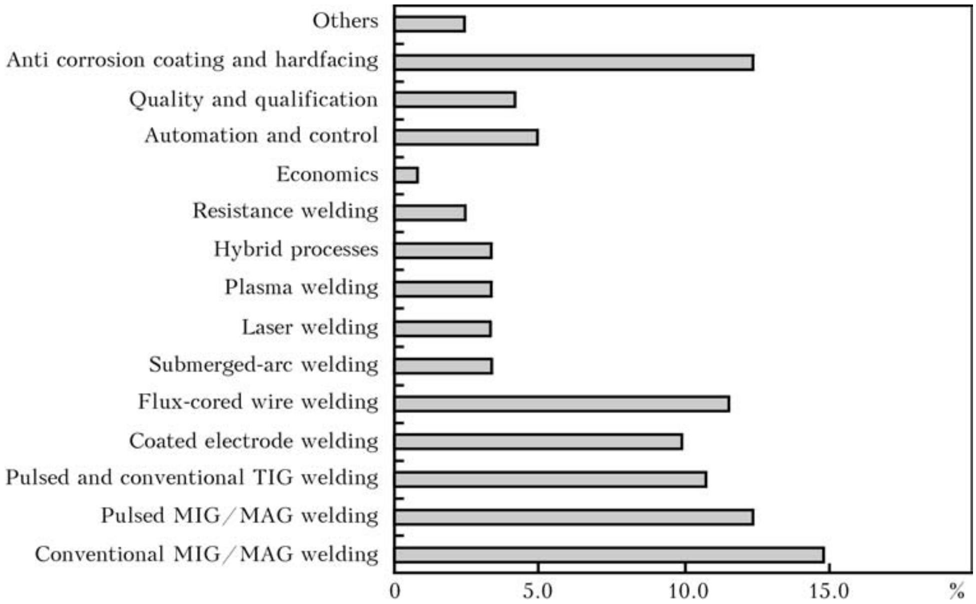

Figure 8. Main aspects on processes studied by the groups in Brazil (responses from only groups that claim to working on welding as first subject)

the South American economy). From the questionnaire output, some characteristics of the work developed by the group working in each site were possible to be raised. The first question was related to the emphasis given to the work carried out by the researching groups. As seen in Figure 6, most people is working on metallurgical aspects of welding (61.5 %). Only around 31 % has welding process as the main emphasis. The second question tried to bring out the main aspects on metallurgy that have been studied by the groups. Figure 7 shows that almost all aspects are covered, but more effort has been put on weldability of stainless steels. Finally, similar question was put to uncover the aspects under investigation related to processes. As seen in Figure 8, the MIG/MAG process (conventional and pulsed) is the main subject for researching. Very little have been done in more modern processes, such as laser, plasma and hybrid processes.

Welding Group of Federal University of Uberlandia. The group denominated Laprosolda, which is an acronym in Portuguese for «Laboratory for Welding Process Development», is one of the groups which work on welding processes (metallurgy is usually a tool for achieving consistent results). This group is part of the Faculty of Mechanical Engineering of Federal University of Uberlandia, which is an average size and reasonable young university (it was federalized in 1995). Uberlandia, in turn, is a prosperous middle-sized city (610,000 inhabitants) located at the center area of Brazil (see Figure 5). Despite of being part of the most industrialized area of Brazil (southeast), Uberlandia does not sustain important metal-mechanical industries (the economy is based more on agro-industry and agribusiness). Regardless, the Mechanical Engineering course of its federal university is one of the best in the country and its post-graduation program in mechanical engineering is one of the 6 at the top in the official rank.

Laprosolda was created in January of 1992, with the objective of developing know-how in Brazil for using less conventional welding processes (pulsed current, double-pulse, plasma, double-wire, controlled short-circuiting, plasma-MIG, etc.). Ever since, the group is in pursuit of, with success, a physical structure and equipments with this aim. In addition, it was set up a staff team to have not only theoretical knowledge, but also understanding of the factory ground reality. Philosophically, involvement with industry was always sought, addressing the researches for applications.

Today, Laprosolda occupies 590 m^2 of dedicated area, distributed in three labs. Lab I (Figure 9) lodges a workshop, administration, staff and student offices, a warehouse, a computational resource room and toilets. Lab II (Figure 10) accommodates another work-

Figure 9. Lab I: *a* — front view of the building; *b* — work-shop; *c* — computational resources room

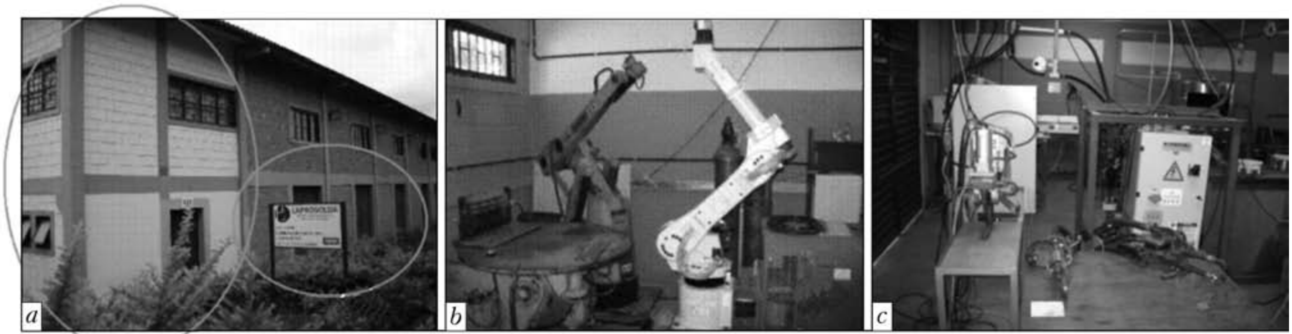

Figure 10. Lab II: *a* — front view of the building; *b* — robot cell; *c* — spot welders (MF/DC and AC)

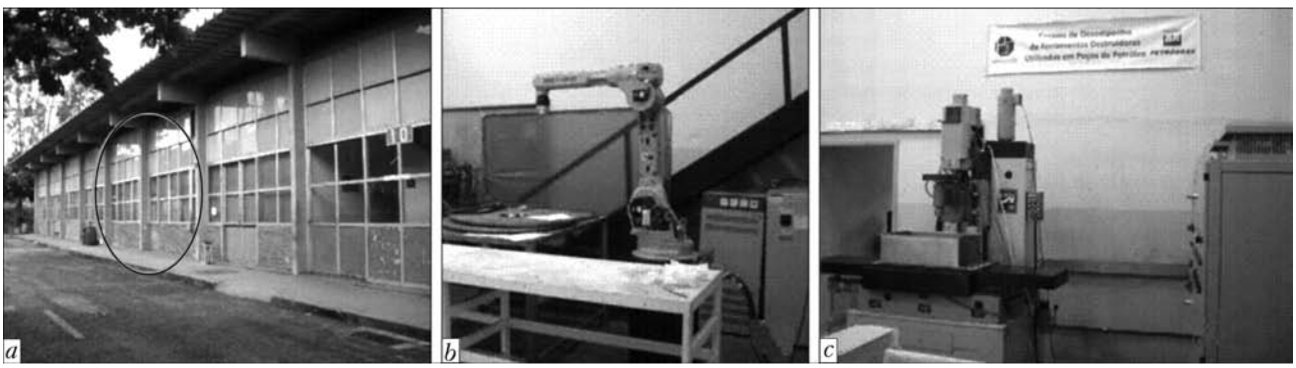

Figure 11. Lab III: *a* — front view of the building; *b* — robot cell; *c* — petrol drill test

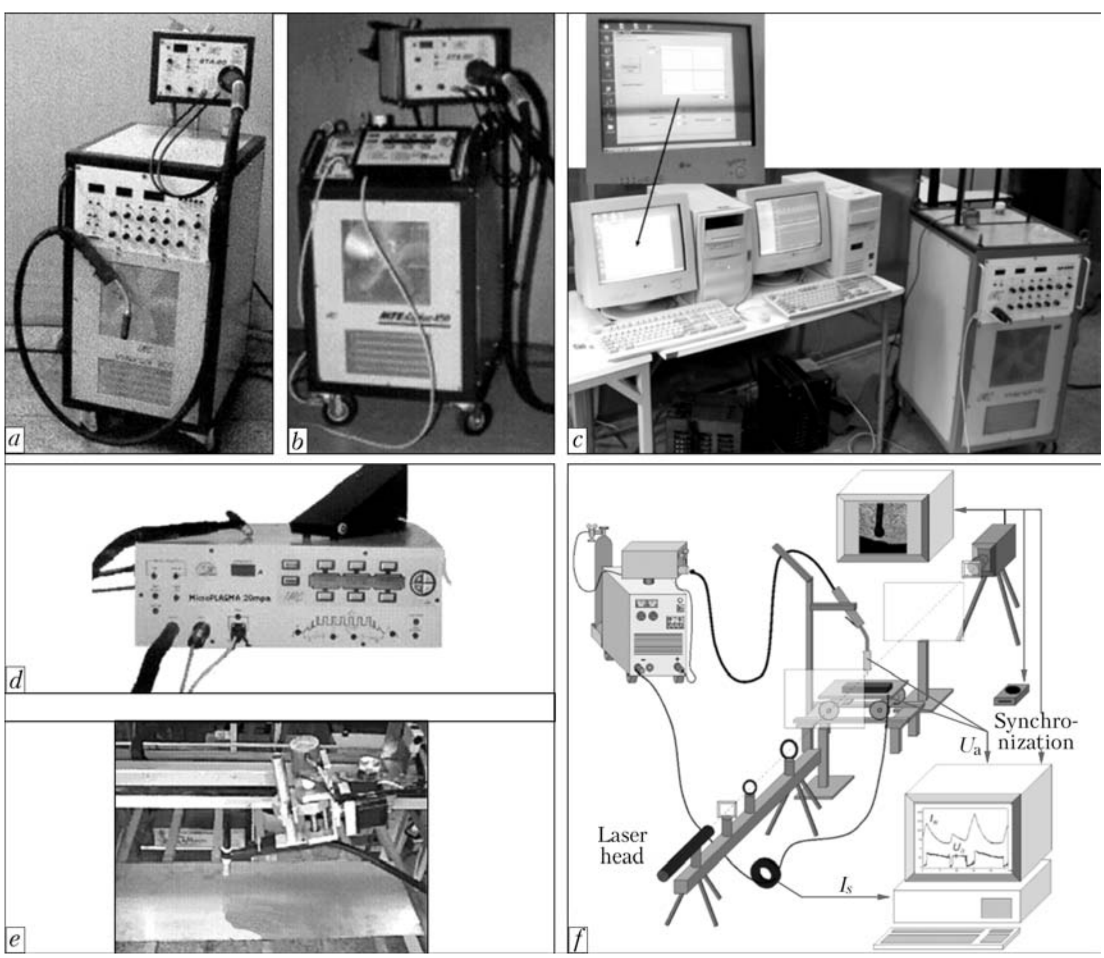

Figure 12. Multiprocess power sources (IMC, Brazil) commanded also by PC (*a*–*b*); a computer commanded power source system for welding with a current/voltage signal drawn in the screen (UFSC, Brazil) (*c*); micro-plasma equipment (*d*); view of the oscillator of a 3D welding table homemade (*e*); schematic view of the shadowgraph system for studying metal transfer (*f*)

shop with a robot cell, fully controlled spot welders (two, one is MF/DC), plasma and oxi-fuel cutting table, conventional arc welders (submerged, coated electrode with a welder simulator, MAG, etc.), warehouse, a space for the MIG orbital rig (under development), staff offices, secretary office, class room and toilets. Finally, Lab III (Figure 11) holds a workshop with another robot cell (20 kg), a rig for testing petrol perforation drills, mechanical test (Charpy and universal tensile) and a wear test (rubber wheel), a metallographic preparation room, a microstructural analyses shop (optical microscopy and micro-hardness) and an electronic workshop. The permanent staff body that conducts the researches is composed of three full time PhD researcher/lecturers (a professor and two associate professors), an engineer and one technician.

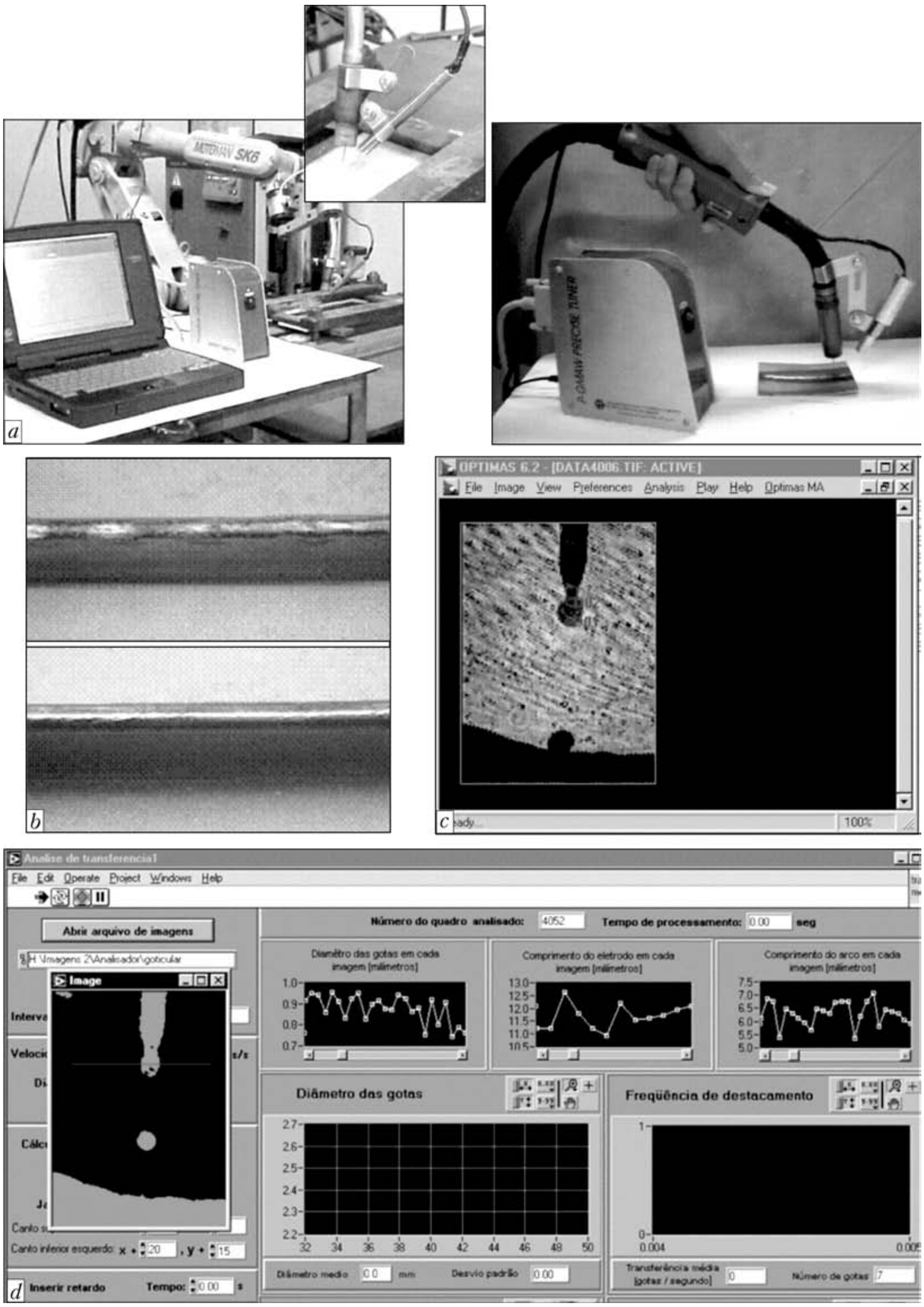

Figure 13. Monitoring (manual welding) and controlling (automatic welding) system for maintain one drop per pulse in pulsed MIG/MAG welding (White Martins (*a*) *b*: *upper* — plasma melt-in weld using argon as plasma gas (travel speed of 600 mm/min), *lower* — similar weld, at same current, using the developed Stargold Flash gas (White Martins), with better finish and higher travel speed (2200 mm/min); a program for measuring dynamically the drop position, speed and acceleration (*c*); a program (Laprosolda) to measure drop frequency, size and arc length along the weld (*d*)

Most researches are developed by undergraduate and graduate (MSc and PhD) students, under supervision, apart from some projects for industry that researchers are hired for determined time. At the moment that this paper was written, the industrial partners were White Martins (Praxair) — welding gas supplier, Petrobras — petrol company, Usiminas — steel maker, Benteler — car part maker, Air Products do Brasil — welding gas supplier and Belgo Bekaert — welding wire manufacturer.

In terms of welding related equipment, besides some multi-process electronic power supplies, one can point out two high-speed cameras and laser lightning systems, which are interfaced (homemade) to work synchronized to up to four electrical signals. These cameras have been the main tool for studying metal transfer and other phenomena, such as the heating up phenomena of resistance spot welding. There are still, amongst others, a welding supplier commanded by computer (which allows the operator do draw on screen, and to impose to the machine, any current/voltage signal profile), gas mixer and analyzer, 3D welding tables, galvanization and aluminum coating thickness measurer, optical emission spectrometer, etc. (Figure 12).

The main field of research and development are: metal transfer phenomena (dynamic and cinematic effects on weld geometry); plasma-MIG welding; controlled short-circuiting welding; AC MIG welding; double-wire MIG/MAG welding; shielding gas behavior; distortion and residual stress (using SYSWELD program). The most significant research outputs are: the ODPP (a system for monitoring and control metal transfer in pulsed MIG welding to maintain one drop per pulse); a special gas blend to melt-in plasma welding; a metal transfer analyzer (computer program to measure, from the high-speed images, droplet size and frequency and arc length); a comprehensive rig for measuring MIG/MAG process stability (with monitoring of contact-tip resistance and temperature, feeding force, wire feeding rate close to the contact-tip by contact less sensor and welding current and voltage); and a special gas blend for double-wire MIG/MAG welding using no pulsing power supplies. The Laprosolda tonic is to study the fundamentals to reach the application (Figure 13).

CONCLUSION

Brazil presents a great potential for augmenting the consumption of welding. The demand, at the same time, for increasing research on welding technology (process and procedure innovation) is a condition the keep the companies installed in Brazil on track with the global market. There are a few research groups working on welding technology concentrated in academic institutions and a growing governmental investment in research (there is no tradition of R&D in the private sector), but most of them have not reached the maturity. The majority of groups is working on metallurgical aspects. But there is a small number of researching groups with capabilities for developing and acquiring know-how on this matter, in spite of the fact that university-industry interaction is still incipient, yet promising.

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WELDING AND JOINING — KEY TECHNOLOGIES FOR THE THIRD MILLENNIUM

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Welding of advanced and modern materials and joining of material combinations create new demands for the welding and joining technologies. During the last ten years the new processes and process variations have been developed, particularly in the fields of arc and beam welding, with the aim to increase the economic efficiency, to reduce the energy input and to assure the quality of the welded joints. The so-called «cold joining technologies» became challenging. The work presents an outline of recent advancements of the welding and joining technologies, and specifies their technical and economical potentials.

Keywords: *key technologies, arc welding, electron beam welding, non-vacuum EBW, laser beam welding, laser-MIG hybrid welding, spot welding, mechanical joining, adhesive bonding, commercial relevance of joining techniques*

There are not many things in our natural environment which have the monolithic structure and the beauty of a rock crystal. Most things of our environment are, for that matter, composed of many individual parts and those parts must be joined to one piece — be it immovable or movable — in order to fulfil their function as a structural part.

Three recognized key technologies and their relatedness to joining techniques shall be considered.

The first key technology is «Traffic» (Figure 1). A car is composed of many single parts which are kept together by thousands of welding spots and many metres of weld seams and, nowadays, more and more by hundreds of meters of adhesive bonds. Vehicles which are used for rail traffic like, for example, an ICE high speed train wagon, are, of course, welded. The ICE wagon has a length of more than 20 m and is composed of more than twenty individual extruded profiles which are welded together with the suitable joining technologies. Interestingly, the window openings are cut out with the laser only after the wagon has been welded completely. In air traffic the mainly used technique is riveting; for the new airbus 380, however, a large part of outer hull elements has been welded, for the first time with the laser. A cruise ship consists of more than 300,000 single parts, and 900 km of welding seams must be welded for assembling the ship. Nowadays, but also when looking ahead, the key technology «traffic» is, in conclusion, not imaginable without the application of welding.

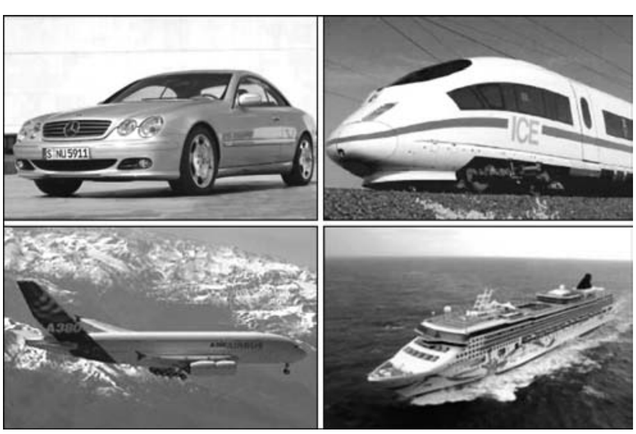

Figure 1. «Traffic» key technology

The second key technology is power- and civil engineering. A power plant produces energy. For the generation of profitable and that means highly efficient energy the so-called steam parameters are important: a highest possible pressure with, at the same time, high steam temperatures. The boilers, pipes and turbines must be capable to tolerate those high pressures and temperatures. This is only possible through the selection of suitable materials and joining techniques. In the field of chemical apparatus engineering, corrosion susceptibility creates extremely challenging tasks. Aggressive media, like acids and bases, mainly in processes with extremely high pressures and extremely low or high temperatures, are dealt with only through the application of special materials which again make extremely high demands on the joining technique. It also applies to the field of civil engineering that steel structures are, of course, not accomplished without welding, as the picture of the Oresund bridge shows. But even if the used steel is not visible, think of concrete highrises, massive steel structures inside the highrises are responsible for the strength and safety of those buildings, and it goes without saying that the steel has been welded. Without welding, power- and civil engineering would also be impossible to realise.

The third key technology is the microsystems technique. Smallest, sometimes no longer visible sub-assemblies (modules) must be joined. Modern electronics and computer technology are nowadays just unthinkable without the use of sophisticated brazing techniques. Thousands of brazing spots on a most confined space are necessary to make a computer work, a mobile phone has more than thousand brazing spots and would, of course, not work without them. The sensors, actors and chips have all been joined with most different technologies. The microsystems technique is not accomplishable without using joining technology and will, also in future, not be possible.

The joining technique is capable to bridge nine dimensions, from 10^3 up to 10^{-6}; the modern joining technique provides technologies which are absolutely indispensable — and this covers the range from ship to chip. The joining techniques belong to the key technologies for the future.

Nature itself has created versatile joining techniques. The cross spider's web, a termite hill or the sundew are just representing a few examples. Also with regard to utilisation by humans, the joining technology is an ancient technology. Artefacts from Mesopotamia, dating back to 2,500 B.C., have shown that joining techniques had been used already for creating jewellery or basic commodities. Artefacts from all over the world, from China, Europe or South America are documenting the worldwide and early application of the joining technique. Modern welding techniques have been first applied at around 1850 with the use of an oxyacetylene flame (acetylene and oxygen) for the fusion of the materials to be joined. By the end of the 19th century for the first time the energy of an electric arc had been used for melting the materials (Figure 2). These methods are still existing to this day and they have in the past been constantly improved and modified.

Welding processes. *Trends in arc welding processes*. In the early sixties, GMA welding methods were introduced into industrial manufacturing and they have been consequently developed further ever since. Great efforts have been made to increase deposition rates and with this increasing efficiency and welding speeds and decreasing heat input by extending the frontiers of known processes and by developing new ones.

GMA welding processes. Modern electronics and computer control as well as improvements in wire feeding have led to digitally controlled power with high power/weight ratios with new features. Digital controllers allow the flexible implementing of several, very different power source characteristics containing complex control strategies. Pulsed arc welding control strategies have been improved concerning process stability and avoiding and recovery from short circuits. Using digital controllers makes interfacing to external computers a lot easier, so that modern power sources provide multiple functions for adjusting process characteristics, parameter development and documentation and as well as for quality assurance.

These machines allow the use of all stable welding processes beginning with the well-known short arc welding process up to the high deposition welding processes such as the rotating-arc and high-deposition spray arc welding processes.

Two-wire welding. GMA welding with one wire has, applying the mentioned types of arc, reached operating ranges, that probably can not be extended significantly by further developments of power-sources, filler materials or shielding gases. Literature mentions welding speeds of up to 2 m/min for high

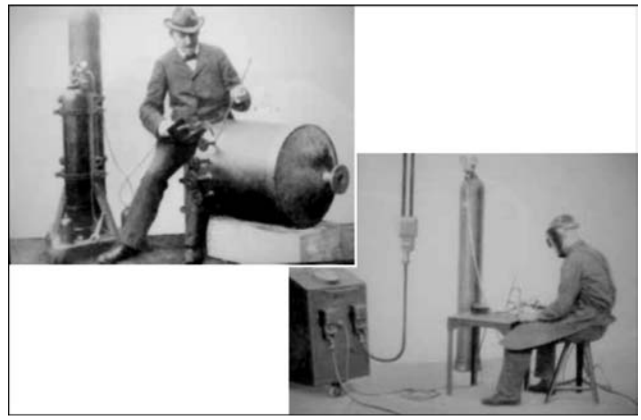

Figure 2. Beginning of modern joining technology

deposition short arc welding, as well as deposition rates of up to 14 kg/h for the rotating arc. A further increase in deposition efficiency is, among other reasons, limited by the instable arc rotation.

This and the need for high deposition rates with reduced heat input led to the development of the two-wire GMAW technology, combining two wire electrodes in one common gas nozzle. Early investigations on this field carried out in the 1975 failed as the power source technology at that time was not able to maintain a stable welding process. The application of a new generation of power sources, however, was able to overcome the witnessed difficulties and establish two-wire welding in two variations as a promising new production method in industry. Employing a second process has significant influence on the shape of the weld pool. Arranging the electrodes behind each other stretches the welding pool in the direction of the welding speed. The leading wire then causes adequate penetration while bead shape is determined by the trailing wire electrode. The longed weld pool allows better degasification, a fact which, especially in welding of aluminium and in welding through primer coatings, reduces porosity sensitivity. Twisting the electrodes slightly into a position next to each other enhances bridging abilities at reduced current levels. This, however, affects the weld speed. A twist by about 20° requires a reduction of weld speed by about 25–30 %.

Two-wire GMAW processes are divided into two variants, twin GMA welding, which is the older process employing a common contact tube and tandem GMA welding, which uses electrically isolated contact tubes for each wire.

Twin GMA technology. Developments started with the twin GMAW technology, which is characterised by a common contact tube connected to one (or two coupled) power source. This results into the same voltage being applied to both wire electrodes. As two equi-directional current-carrying conductors are attracted to each other due to the magnetic forces, the arc roots of both electrodes form (depending on the distance between them) a common root. At a spacing of 4 to 7 mm, depending on wire diameter and total current intensity, the detached droplets meet in one common weld pool. Smaller distances may lead

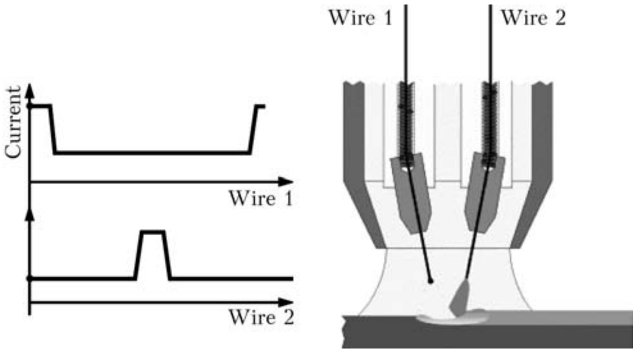

Figure 3. Tandem GMA welding technology

to a droplet bridge between both electrodes, causing process instabilities. In case of a too large distance between the wires, to separate weld pools occur and because of heavy blow effects, heavy spatter occurs.

Main disadvantage of this process variant is that the welding parameters can not be set independently for each electrode, so that individual wire speeds and wire diameters cannot be used. Moreover, short circuiting of one arc will extinguish the other because of the common contact tube, making the overall process instable. This limits twin GMA welding to non-short circuiting processes such as spray-arc or pulsed arc.

Tandem GMA welding. In order to optimise process behaviour and to be able to control both arcs separately, torches with electrically isolated contact tubes are used and synchronized independently controllable power sources are employed (Figure 3). Such it is possible to use this process in short arc welding and to use different wire diameters and speeds, were necessary, featuring stable welding processes.

AC-MIG welding. The need for lighter constructions leads to the use of thinner sheets, which in turn, results in difficult gap bridging ability. When GMA welding with reverse polarity, heat input into the base material as well as penetration is reduced and the ability to bridge gaps improves. Unfortunately process stability is bad with reverse polarity. AC-MIG powers sources combine a standard pulse process with an adjustable phase of reverse polarity. This leads to a stable welding process with adjustable penetration and gap bridging ability highly suited for thin sheets with gaps as often found in industrial applications.

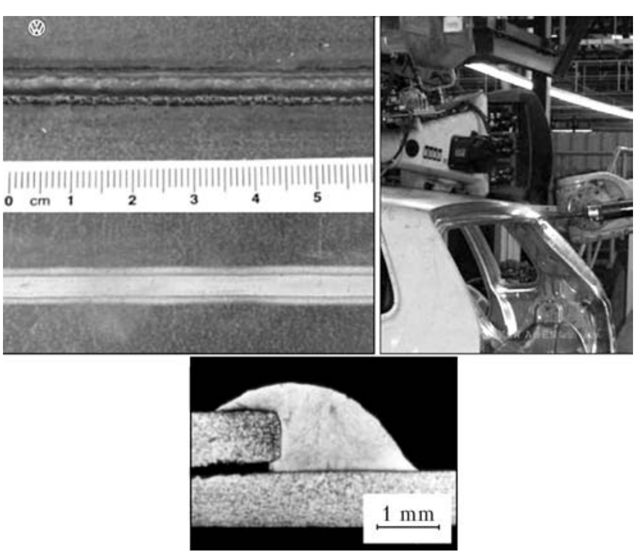

Figure 4. GMA brazing (consumable: $CuSi_3$, diameter 1 mm; shielding gas Ar + 0.5 % O_2; 15 l/min; brazing speed 100 cm/min; energy input 546.6 J/cm)

CMT processes. CMT is the abbreviation for «cold metal transfer» and specifies a GMAW process with a very low heat input, in comparison with the conventional short-arc process.

In the conventional short-arc process, the wire is continuously fed. At the moment of the short-circuit, the current increases strongly and is responsible for the circuit breaking and for arc re-ignition. The high current intensity at the moment of arc re-ignition and the rather uncontrolled breaking of the circuit causes increased spattering.

In a CMT process the wire is not only moved into the direction of the workpiece but also, with oscillating wire movement and frequencies of up to 70 Hz, withdrawn from the workpiece. The wire movement is thus a part of the process control. The short-arc current of the CMT process is very low, the material transfer occurs with a current of almost zero. The short-circuit is, in addition, not breaking uncontrolled but is effected and controlled by the wire withdrawal. Both properties cause a low energy input with practically spatter-free welded and brazed seams.

The main application fields of the CMT process are: spatter-free MIG brazing, thin sheet welding (aluminium, steel and high-grade steel) and arc joining of steel with aluminium.

GMA brazing. The principle difference between GMA welding and GMA brazing lies in the field of metallurgy. When welding, a certain amount of penetration is desired, to ensure fusion between base material and steel filler material. In brazing, there should be no melting of base material, if possible. GMA brazing equipment is the same as for GMA welding, merely a low-melting copper base bronze wire (900–1100 °C) is used. Processes used are short arc as well as pulsed arc.

GMA brazing has already become well established as a method for joining galvanised thin sheets. As no base material should be melted, heat input into the material is minimised and damage to the zinc coating is limited to a minimum with no negative influence on corrosion properties (Figure 4).

The strength of the brazing joints is comparable to that of welds. Moreover, finishing of the brazed seam is easy. Due to this, GMA brazing is becoming more and more popular not only for car body building in automotive industry but everywhere where the advantages of low heat input, low distortion, less damage to galvanised coatings and high brazing speeds outrule the higher price of the required bronze electrode.

Plasma-MIG welding. Plasma-MIG welding is a welding process, that is experiencing a revival after being developed as a high deposition process in the past. New torch technology as well as modern power sources are the reason for this. The plasma-MIG process is a standard MIG process with a concentric plasma torch around it. Both processes are controlled by separate power sources. As the plasma process stabilises the MIG process and vice versa, parameters for both of them can be varied in a wide range. Thus possible applications reach from high deposition aluminium and steel welding, making use from the wire preheating and the extra heat input from the plasma process to highly stable medium deposition processes with the extra benefit, that the additional plasma cleans the surface directly before material is deposited with benefits in aluminium welding down to plasma-MIG brazing with very low heat inputs and the possibility of influencing bead shape.

Developments in beam-welding processes. *Electron beam welding*. The range of joining tasks for electron beam welding reaches from foil welding with plate thickness of just a few 1/10 mm up to thick plate welding with achievable weld depths of 150 mm. Moreover, almost all electrically conductive materials are weldable, many of those materials may also be joined in material combinations. The high power density in the range from up to 10^8 W/cm^2 which is typical of electron beam welding and the connected dept-to-width ratio of the weld (up to 50:1) allows a large variety of possible applications of this joining process.

Standard electron beam welding is normally carried out in a vacuum chamber under high- or low-vacuum, but there is also the possibility to use the electron beam in a free atmosphere.

In automotive industry, electron beam welding in vacuum is mainly used for engine and gear parts. The non-vacuum (NV-EBW) method is mainly used for the joining of plates; filler material is frequently applied and allows high gap bridging abilities.

Non-vacuum electron beam welding. As in electron beam welding in free atmosphere (NV-EBW) a vacuum chamber is not necessary and thus evacuation times as well as chamber-conditioned restrictions to the component dimensions may be set aside, this method is most advantageous. The technique has been developed in Germany in the sixties. The beam generators are of the same design as those in vacuum-EBW. Figure 5 shows a NV-EBW generator and a typical application.

The half-shells of the depicted aluminium hollow-sections are joined by the NV-EBW method. Welding speeds of up to 12 m/min are applied which makes NV-EBW also a highly profitable method. There are further reasons, besides the high welding speed, which make NV-EBW applications highly recommendable.

In comparison with laser beam welding methods which, for many applications, are directly competing with NV-EBW methods, the electron beam is able to penetrate the workpiece surface independently from angles or surfaces. After leaving the beam generator, the beam is guided into ranges of higher pressure right to atmospheric pressure. Series-connected chambers generate the drop of pressure. The beam is focused onto the exit nozzle which has a diameter of 1–2 mm. With rising ambient pressure the electron beam is scattered through a collision with gas molecules and enlarges. In free atmosphere the beam maintains its initial power density over a short length only. During welding, a maximum working distance of approximately 25 mm must not be exceeded.

The beam diameter is between 1.5 and 2.5 mm, depending on the working distance and the accelerating voltage. This focused spot which is, compared with vacuum-EBW and laser beam welding relatively large, allows a good gap bridging ability and a relatively coarse edge preparation in a combination with filler material.

The utilisation of the energy density of the electron beam in free atmosphere and the high available machine powers allow to achieve weld speeds of 20 m/min with steel materials and more than 50 m/min with aluminium alloys.

Laser beam welding. Laser beam welds are characterised by a high depth-to-width ratio, resulting in a minimum influence on material properties and high welding speeds. On the other hand, the demands on seam preparation and positioning are high and gap bridging ability is low. Recent developments mainly focus on optimising gap bridging ability and welding time and to lower demands on seam preparation and positioning.

Laser beam welding with filler wire. Adding a precise wire feeding device to the standard laser process is the simplest extension. By adding filler material, it is possible to fill gaps and take influence on the metallurgy of the weld. This qualifies laser beam welding with filler wire also for material combinations with intermediate layers as well as for materials tending to crack.

Laser-MIG hybrid welding is the combination of a laser welding process and a standard GMAW process in one common welding zone. It combines the deep penetration of the laser beam welding process with the good gap bridging ability of GMA welding. Furthermore, the laser process stabilises the GMAW proc-

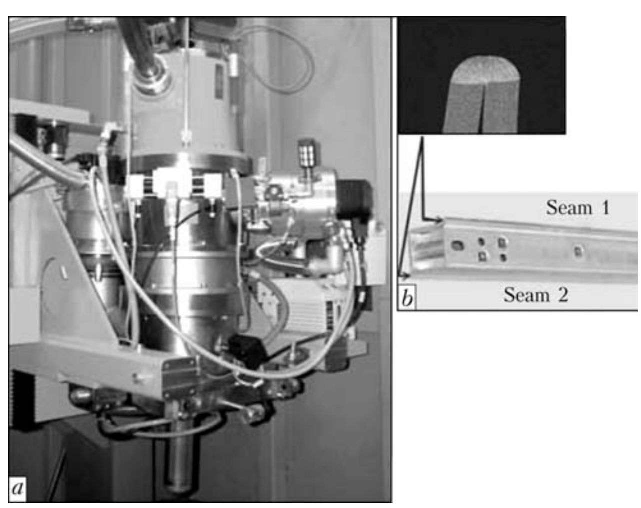

Figure 5. NV-EBW gun (*a*) and welded aluminium hollow-sections (*b*)

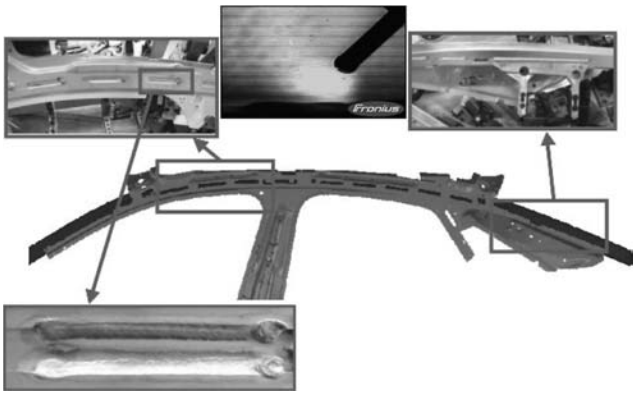

Figure 6. Laser-MIG hybrid welding of car roof structure

ess. As filler material is applied as a liquid, high welding speeds can be achieved with low heat inputs. Applications for laser-MIG hybrid welding are steel (CO_2-lasers) and lightweight alloys (Nd:YAG-lasers), plates thickness start from car body sheets and are limited by the available laser power. A rule of thumb estimates 1 mm plate thickness per 1 kW CO_2-laser power for steel. First industrial applications in automotive industry are in the production of aluminium car bodies (Figure 6).

Remote welding. When replacing spot welds by laser welds, this is usually done by short welds, that require long travel times between the welds when carried out with robot guided laser optics. To reduce these travel times, it is necessary to reduce the moved mass, only deflecting the laser beam itself is the ideal case. The principle of remote welding shows, one or two mirrors deflect the laser beam, positioning the focus in height direction is done by moving the long focus focussing lens along the axis of the beam.

The realisation of remote welding was only possible with a new laser generation with optimum beam quality such as CO_2-slab-laser. Together with a focussing lens of 1600 mm, this opens a considerable working field, which may be enhanced by mounting the remote welding unit to a 3D-robot. With remote welding, the travel time between the welds may be reduced to a few 1/100 s reducing welding time by up to 25 %.

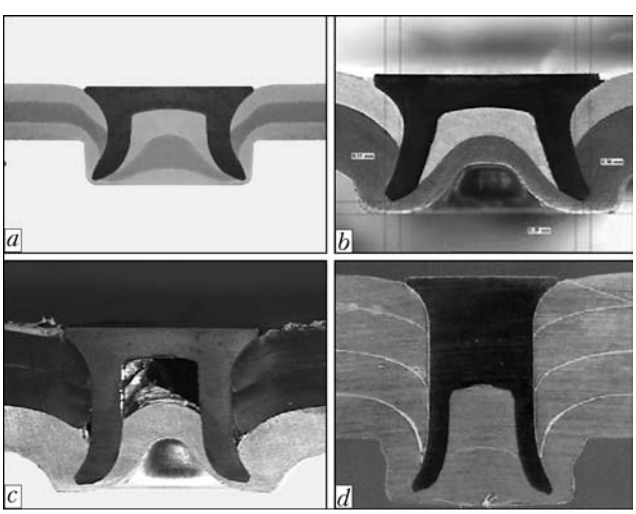

Figure 7. Punch riveting: *a* — Al–steel–Al; *b* — Al–steel; *c* — Al–plastics; *d* — Al–(1.5 + 2 + 2 + 2) mm

Spot welding. High strength steels, as they will be employed in the future generations of car bodies, require modifications of the existing spot welding technology. The main concern here lies in the use of special force/movement programs with higher forces, as they can be applied with present pneumatic or hydraulic welding equipment.

Resulting from this, new electro-mechanic welding devices are being developed, that are capable of applying the required higher welding forces. Their capabilities are currently evaluated.

«Cold» joining technologies. The combination of different material types, may they be steels, lightweight alloys or polymers, between each other require joining processes different from the classic thermal welding processes. Mechanical joining processes and adhesive bonding are gaining increasing importance with the increasing applications of these materials.

Mechanical joining. Not only in multi-material constructions but also for the spotwise joining of aluminium clinching and punch riveting are applied in increasing numbers. Clinching does not require additional parts such as rivets to join plates. A disadvantage of this process is the low crash strength and its restriction to materials of lower strength grades. Punch riveting reaches strength levels comparable to spot welding. Typical for this variant is the use of an additional rivet, that cuts through the plates (Figure 7).

Advantages for both clinching and punch riveting are the low distortion and the ability of joining different materials. They can replace spotwelds in some cases.

Adhesive bonding. Structural adhesive bonding is gaining importance in car body building for a few years now. Advantages are seen in the two-dimensional force transmission, resulting in better stiffness and crash properties of the joined structures. Adhesive bonding is normally combined with other joining processes such as clinching, punch riveting or spot welding.

Simulation of joining techniques. The reduction of development time for new car models, the need of cost reduction and increasing safety demands in turn increase the necessity of sophisticated simulation tools. Simulation has become an important helper to learn about product properties, to optimise construction details and production processes, as well as to reduce development and product costs and enhance product quality.

A recourse is to simulate welding and joining processes through a set of mathematical equations representing the essential physical processes of welding. The activities of welding modelling proceed the following directions, associated with the different physical phenomena, which occur during welding with GMA, TIG, beam and spot welding processes: heat source — metal interaction; heat and fluid flow; weld solidification microstructure; phase transformation/weld microstructure; residual stresses and distortions; mechanical properties and integrity; weld geometry.

Several simulation programmes have been developed to compute one or more of the named outputs. Work is still in progress. Future ambitions result in linking the output of these simulation programs to design and calculation software and planning systems in order to get an overall virtual view of all aspects of automobile design, testing and production.

Commercial relevance of joining techniques. The recent study «Macroeconomical and sectoral creation of value from production and application of joining techniques» which, at the instigation of the German Welding Society (DVS), has been drawn up by the Hochschule Niederrhein, Mrs. Professor Moss, for the fair «Welding and Cutting» in 2005, shows the direct and also the indirect creation of value, gained from applications of joining technology.

In Germany, the direct creation of value through the application of joining techniques for devices, filler materials, gases, adhesives, occupational safety and professional training amounts to approx. 3.6 bln euro. This amount has been calculated only conservatively since many joining methods are, statistically, hard to apply. Germany holds approximately one third of the European market share for joining technologies; Europe, on the other hand, holds approximately one third of the world market share — this means that from 3.6 bln euro from Germany a value creation of approximately 11 bln euro for Europe, and, worldwide, a value creation of 33 bln euro can be extrapolated.

Since the joining technique is an interdisciplinary technology which is used within the range of the entire national economy it is important to realize the quantity of the value creation in the manufacturing sector using joining techniques. Following again conservative estimations, these are about 27 bln euro in Germany which conforms to approximately 4.8 % of the total value creation by the German manufacturing industry.

Approximately 640,000 jobholders are, in Germany, working in the field of joining technologies; this conforms to approximately 6 % of all jobholders in the manufacturing industry. Every 16th working place in the manufacturing industry is provided by the application of joining technologies.

CONCLUSION

Joining is an interdisciplinary, sophisticated and indispensable technology. Joining technique is a key technology and will, also in future, remain a key technology for the third millennium.

Joining technologies are interesting and fascinating and, despite many novel developments in recent years there is still a lot of work to be done in future.

DEFORMATION-ENERGY ASPECTS AND PRACTICAL APPLICATIONS OF EXPLOSION WELDING PROCESS

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Deformation-energy aspects of explosion welding processes have been analyzed. The established functional correlation between the parameters of this process in combination with the developed mathematical models, enables controlling the energy and temperature-time conditions in the joint zone and formation of the required structure and properties in the produced composite materials. Examples of effective application of explosion welding are given.

Keywords: *explosion welding, laminated composite materials, plastic deformation, energy balance, process control*

Progress in many industrial sectors (and particularly, in such science- and material-intensive sectors as aerospace and power engineering, oil- and gas mining and processing engineering, electrometallurgy, etc.) is directly related to a wide introduction of advanced materials, which combine high performance, adaptability to fabrication and low production cost. Problems of development of new advanced materials, in particular, metal laminated composite materials (LCM) always were among the main scientific-technological priorities of our state. In view of its inherent features, explosion welding is one of the effective ways to produce high-quality LCM of various types and purposes. Industry need for such materials is growing intensively, which requires organizing modern commercial production, oriented to manufacture of a broad range of composites.

In explosion welding the joint forms as a result of deformation impact on the materials being joined, which is characterized by a high velocity of their collision at short process duration, and which causes two-stage topochemical reaction, as a result of which the final properties of the produced joints are determined by the extent, nature and duration of deformation. This allows regarding explosion welding as a conventional controllable process, which for a number of structures and material combinations is the only technological solution allowing sound joints to be produced.

Considerable success in understanding this complex process has been achieved owing to investigations of a number of Russian and foreign scientists [1–9, etc.]. They have theoretically and experimentally revealed the main regularities of the studied process, studied the influence of the main welding parameters on the properties of the produced joints, plotted the energy balance of explosion welding of two- and multilayer composite materials, generalized the boundary conditions of explosion welding, etc.

Analysis of the nature of formation of solid-phase welded joint of metals, which includes explosion welding, showed that high-rate deformation processes running in the near-weld zone metal have a decisive role in formation of physical contact, activation of the surfaces being welded and, eventually, bonding of metals, which is in keeping with the fundamentals of the general theory of pressure welding formed in Reference [10–13, etc.].

Based on numerous theoretical and experimental data [14–17, etc.] it was proved that the plastic shear deformation of metal in the near-weld zone, which is distributed exponentially across the thickness of the blanks being welded and reaches 100 % near the joint line, has the decisive role in welded joint formation (Figure 1), and the degree of near-weld zone metal involvement into the deformation process essentially depends on welding parameters — velocities of contact v_{con} and collision v_{col} (Figure 1), as well as on the dynamic angle of collision γ.

Generalization of a large amount of experimental data showed that plastic shear deformation g_{max} in the direct vicinity of the interphase of welded composite layers, as well as the thickness of plastically deformed layer y_{def} are directly proportional to the tangential component of collision velocity $v^{\tau}_{col} = v_{col} \sin \gamma$, which depends on the ratio of the collision and contact point speeds (Figure 2).

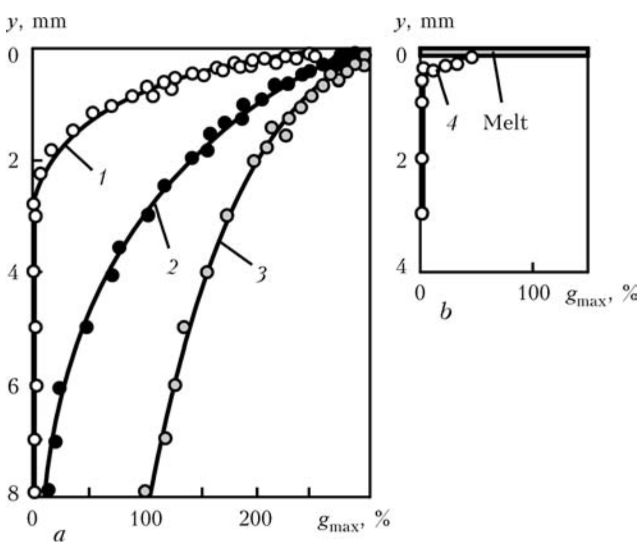

Figure 1. Diagrams of maximum plastic shear deformations g_{max} of near-weld zone metal in aluminium samples welded by explosion in subsonic (*a*) and transonic (*b*) modes [18]: *1* — v_{con} = 1300 m/s, v_{col} = 200 m/s; *2* — v_{con} = 1300 m/s, v_{col} = 420 m/s; *3* — v_{con} = 1500 m/s, v_{col} = 700 m/s; *4* — v_{con} = 4700 m/s, v_{col} = 420 m/s; *y* — distance from the layer boding line in the composite being welded

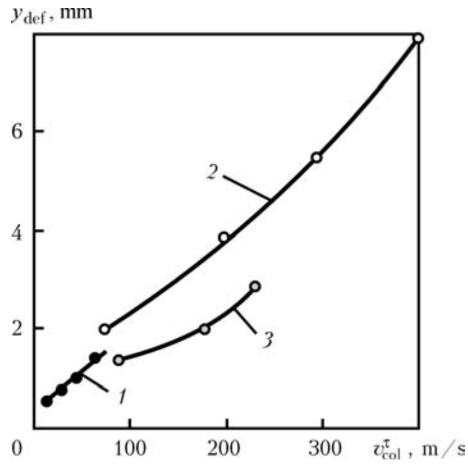

Figure 2. Dependence of deformed layer thickness y_{def} on the tangential component of collision velocity v_{col} [18]: *1* — copper; *2* — aluminium; *3* — steel St3

It is established that the near-weld zone of joints with a wavy profile (unlike the wavefree joints) is characterized by an essential non-homogeneity of the field of residual shear deformation not only across the thickness of welded elements, but also in the direction of the vector of contact point velocity. This is manifested in alternation of metal zones with different g_{max} level (Figure 3). The above feature of plastic metal flow is accounted for by formation of deformation hump not only due to the surface, but also in-depth metal layers in front of the contact point, this leading to their more intensive deformation under of the wave crest. In the zones adjacent to the depression, intensive plastic flowing of the metal is difficult [16, 18].

In welding of dissimilar metals the nature of plastic flow of metal in the near-weld zone of the joint has certain features, associated, primarily, with the difference in their physico-mechanical properties. It is

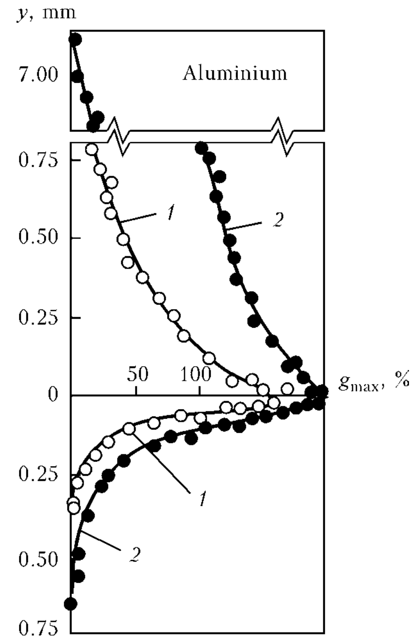

Figure 4. Diagrams of maximum shear in the near-weld zone of explosion welded copper-aluminium combinations at v_{con} = = 1600 m/s [17, 18]: *1* — v_{col} = 200; *2* — 350 m/s

established that the degree of localizing of plastic shear deformations in the near-weld zone of the stronger plate is essentially higher than in the aluminium one. This is quantitatively manifested in different thickness of the deformed layers of different metals (Figure 4).

Obtained extensive experimental data on the nature of variation of plastic deformations across the thickness of the plates being welded, allowed evaluation of the conditions of formation of similar and dissimilar metal joints, as well as calculation of the curves of the initial temperature fields for an arbitrary section of the welded bimetal samples from dissimilar materials. The thermal pattern in the near-weld zone of explosion welded joints of dissimilar metals was

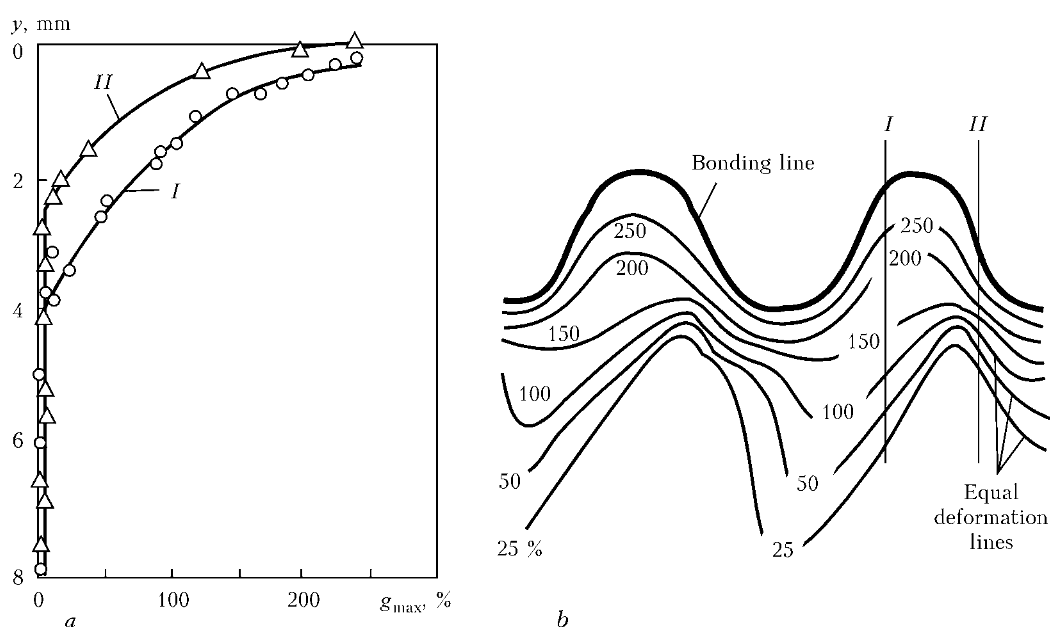

Figure 3. Diagrams of maximum shear (*a*) and equal deformation lines (*b*) in the joint of aluminium plates with the wave-like profile of the joint zone [16, 18]: *I*, *II* — wave cross-sections

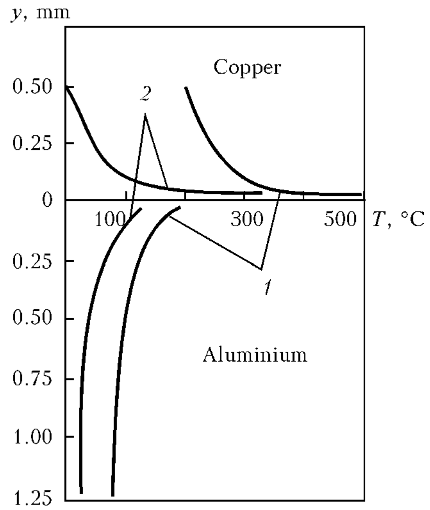

Figure 5. Temperature distribution in the section of a sample of copper-aluminium composite produced by explosion welding [18]: *1* — v_{con} = 2600 m/s, v_{col} = 350 m/s; *2* — v_{con} = 2000 m/s, v_{col} = = 200 m/s

assessed with plotting of initial temperature fields (Figure 5), allowing for the proportionality of the heat evolving in some arbitrary metal layer to the elementary work of deformation, as well as assuming that heat evolves simultaneously in all the layers. Conducted analysis shows that concentration of plastic deformation in the narrow near-weld zone of the stronger material of the welded pair leads to heating of its near-contact layers to a higher temperature, and, as a consequence, to possible surface melting (at intensification of the collision modes) of the less strong, and, usually, less high temperature-resistant material of the welded pair, predominantly due to this heat.

Such phenomena are observed practically in explosion welding of all the compositions of dissimilar materials with markedly different physico-mechanical properties, for instance aluminium to steel, aluminium to titanium, etc.

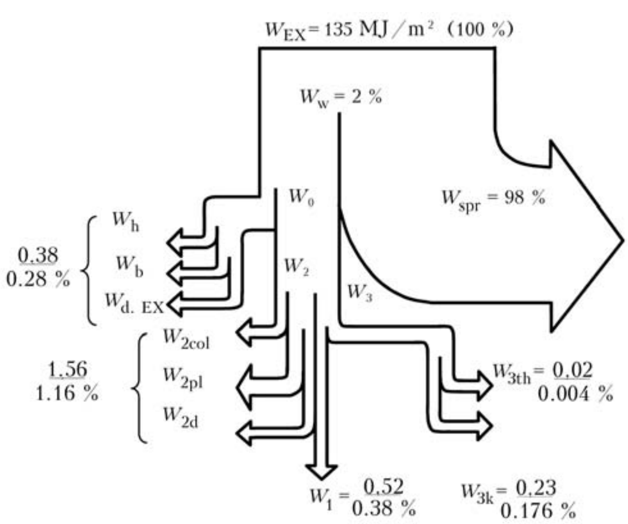

Figure 6. Energy balance in the system of two colliding steel plates (5 mm flyer plate, 18 mm target plate) at v_{col} = 350 m/s, v_{con} = = 2 km/s (values in the numerator are given in MJ/m^2, values in the denominator are a percentage of explosive energy taken to be 100 %)

An important scientific result of experimental research conducted at Volgograd State Technical University (VolgSTU), and allowing correlation of the parameters of the process of high-velocity collision of metals and their initial physico-mechanical properties with the strength characteristics of the produced joints, was construction of energy balance of explosion welding of two- and multilayered metal composite materials with a detailed description of the energy consumption components in the explosion transformation and evaluation of process efficiency [19—21]. It is established that the energy parameters, determining the level and nature of plastic flow, and, therefore, controlling the processes of activation and bonding, allow control of this process on the macrolevel. In the generalized form the energy balance of the system of colliding plates relating the parameters of the two different groups, looks as follows [19]:

$$W = W_1 + W_2 + W_3, \quad (1)$$

$$W = \frac{m_1 v_{col}^2}{2}; \quad (2)$$

$$W_1 = \frac{m_1^2 v_{col}^2}{2(m_1 + m_2)}; \quad (3)$$

$$W_2 = \frac{\tilde{m} v_{col}}{2}\left[1 - \left(\frac{v_{con}}{c_0}\right)^2\right]; \quad (4)$$

$$W_2 = \frac{\tilde{m} v_{col}}{2}\left(\frac{v_{con}}{c_0}\right)^2, \quad (5)$$

where W is the specific (referred to unit area) kinetic energy of collision of elements being welded; W_1 is the specific residual kinetic energy of the system of welded plates; W_2, W_3 is the specific energy consumed in plastic deformation of metal and in cumulation; $m = m_1 m_2/(m_1 + m_2)$ is the averaged weight of welded layers; m_1, m_2 is the specific weight of the flyer and target plate, respectively.

Having conducted detailed item-by-item analysis of the explosive energy balance in the system of two obliquely colliding plates, the authors [21] presented it in the full form (Figure 6):

$$W_{EX} = W_w + W_{spr} = (W_h + W_b + W_{d.\,EX}) + + W_1 + (W_{2col} + W_{2pl} + W_{2d}) + + (W_{3k} + W_{3th}) + W_{spr}, \quad (6)$$

where W_w are the energy losses in the welded plates; W_{spr} is the energy of spreading of the explosive detonation product (DP); W_h, W_b are the energies of the flyer plate heating by DP and its double plastic bending; $W_{d.\,EX}$ are the dissipative losses in it from DP impact; W_{2col}, W_{2pl} is the energy of crushing of the microreflief of the colliding surfaces and plastic flow in the collision zone (shear, wave formation); W_{2d} are the dissipative losses in the impact wave due to collision, respectively; W_{3k}, W_{2th} is the kinetic and thermal components of cumulative jet energy, respectively.

All this taken together enabled determination and description of all the main boundaries of this process existence in energy coordinates of averaged weight of welded layers: $\tilde{m}$ — relative velocity of contact point, v_{con}/c_0 is the dynamic angle of collision γ (Figure 7).

Based on numerous experimental data it was proved that for each arbitrary combination of joined metal there exists a certain constant critical value of energy consumed for plastic deformation W_{2cr}, at which equivalent strength is achieved in the welded joint, and its value can be determined through the index of technological deformability of the metal (Figure 8) [20]:

$$W_{2cr} = 0.606 + 0.184 \ln (HB/\delta) \ [\mathrm{MJ/m^2}], \qquad (7)$$

where HB/δ is the ratio of Brinell hardness to relative elongation.

Energy balance in a multilayer system is of an even more complex nature and is extremely important both in scientific and practical terms. It is shown that energy consumption in the system can undergo essential changes and run differently depending on the geometry, collision parameters, ratio of weight characteristics of the layers (Figure 9).

This clears the way to control of the process of formation of sound welded joints on any composite interphase. For instance, in a three-layer composite application of thin interlayers, usually, leads to energy crisis of the first interphase because of small thickness of the layers, which is exactly the factor determining the low strength here. A similar situation, but already on the second interphase, is in place at a great thickness of the intermediate layer.

The extensive theoretical and experimental material accumulated so far, provides conclusive evidence of the fact that during high-velocity collision of metal plates, the work or energy consumed for plastic deformation of near-contact metal volumes, which eventually are responsible for welded joint quality, are determined by the totality of pressure (changing in time) and time during which it is capable of inducing plastic deformation in the metal. It is experimentally established that the time of joint formation τ_j (even in welding of one specific pair of materials) is not constant, but essentially depends on collision velocity v_{col}.

In order to correlate the force impact (pressure) in the collision zone and time of joint formation a new parameter is introduced, namely deforming pressure pulse I_d, the value of which can be, essentially, controlled either by variation of the thickness of welded plates, influencing the time, or by changing the peak pressure in the joint zone through collision velocity v_{col} according to the following dependence:

$$I_d = \int_{\tau_0}^{\tau_w} p_{max} e^{-\tau/\theta} d\tau = p_{max} \theta (1 - e^{-\tau/\theta}), \qquad (8)$$

where p_{max} is the maximum (peak) value in the contact zone; τ_w is the time of pressure impact, which exceeds the dynamic yield point of the materials being welded;

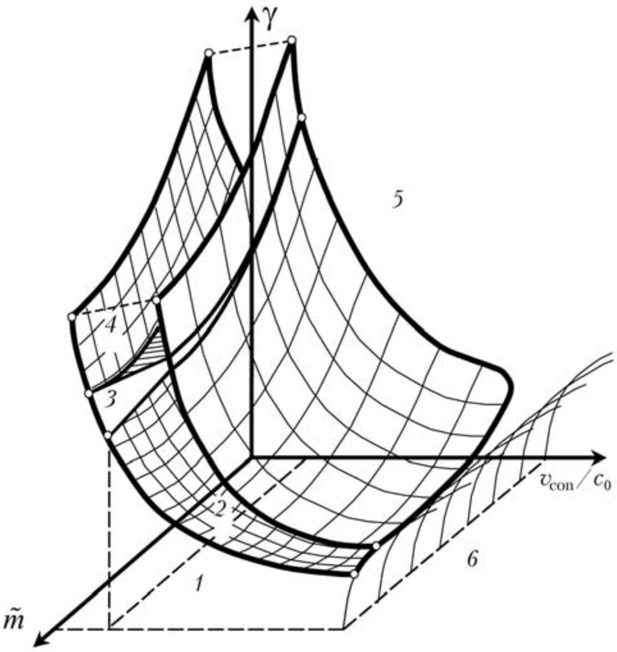

Figure 7. Position of the main characteristic regions of explosion welding of metal in different modes: *1* — subcritical; *2* — «traditional» modes with wave formation; *3* — no wave; *4* — with anomalous wave formation; *5* — developed cumulation; *6* — supersonic

θ is the time constant, dependent on the nature of materials involved in the collision (for low-carbon steel θ = 0.96 μs, for aluminium θ = 0.565 μs).

Addition of this parameter provided a real possibility of explaining and quantitatively describing from a new viewpoint some regularities which are manifested in explosion welding of metals, for instance increase of the dimensions of waves or joint strength at increase of thickness of plates being welded or collision velocity [18]. In addition, parameter I_d allows

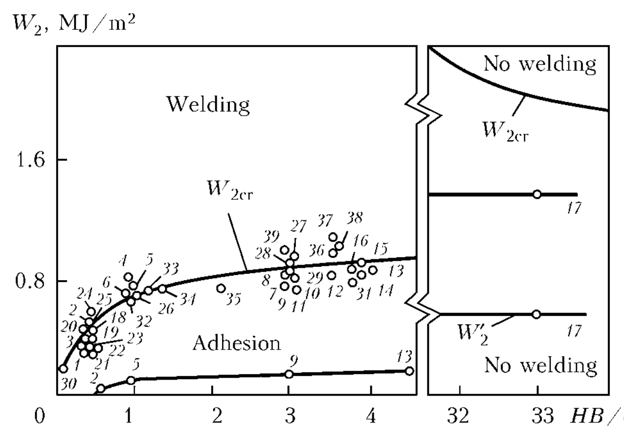

Figure 8. Influence of the index of technological deformability (Astrov's criterion) HB/δ on critical energy of plastic deformation W_{2cr} (points are plotted by the data of various researchers): *1–3, 39* — Al + Al; *4–6* — Cu + Cu; *7–11, 39* — St3 + St3; *12* — Ti + Ti; *13–16* — 12Kh18N10T + 12Kh18N10T steel; *17* — VT20 + VT20 titanium; *18–22* — AD1 aluminuim + 12Kh18N10T steel; *23* — AD1 aluminuim + M1 copper; *24* — Al + St3; *25* — AD1 aluminuim + MA2-1 magnesium; *26* — M1 copper + Kh18N10T steel; *27, 28* — St3 + 5KhV2S steel, St3 + 25KhNMA steel; *29* — Kh18N10T + St3 steel; *30* — Pb + St.3; *31* — Zr + Kh18N10T steel; *32–35* — aluminium alloys + Kh18N10T steel; *36, 37* — St10 + Kh18N10T steel; *38* — VT6 titanium + 10G2SD steel; W_2' — energy corresponding to the start of metal bonding

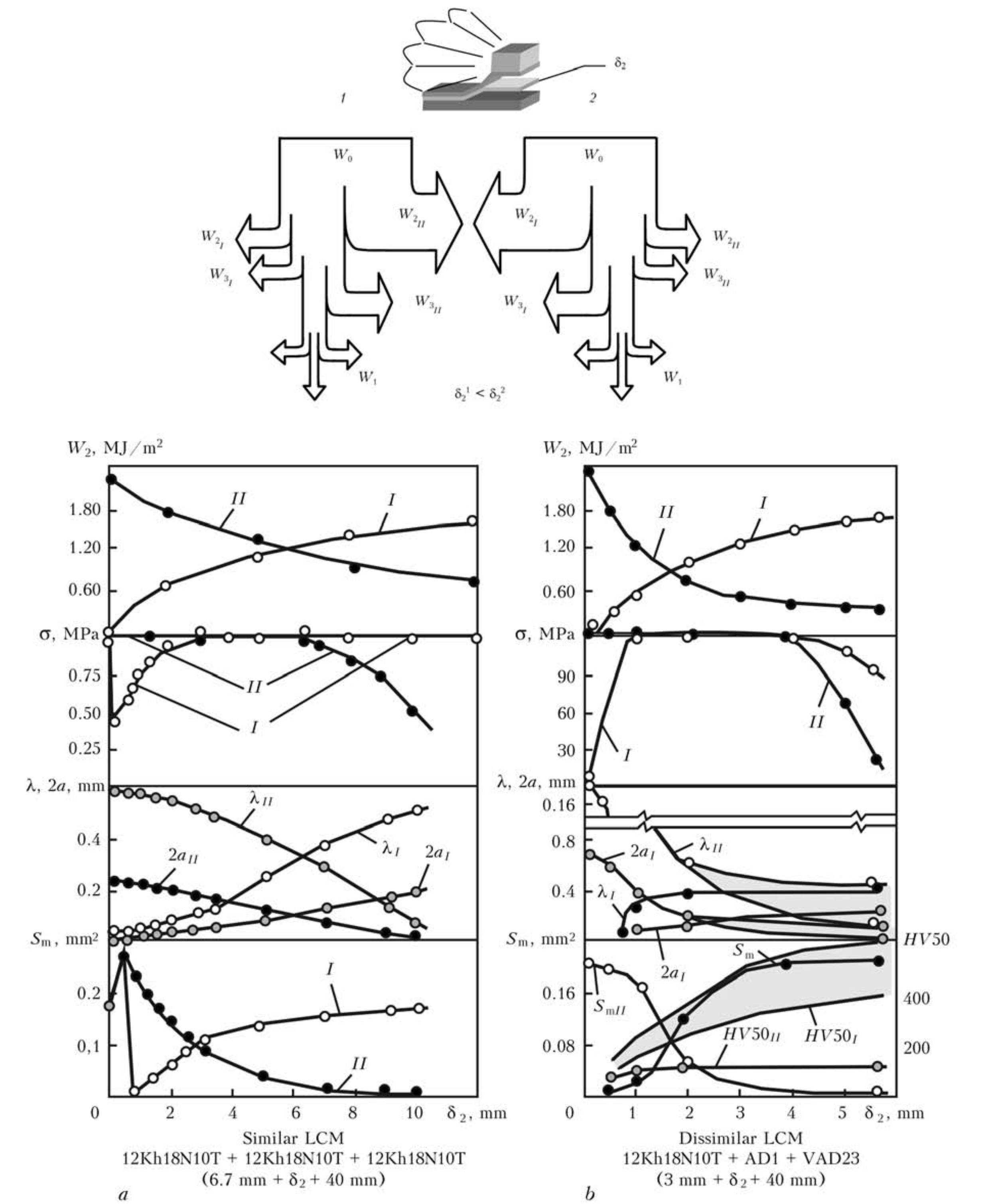

Figure 9. Influence of second layer thickness δ_2 of three-layer steel (*a*) and steel-aluminium (*b*) composites on distribution of energy W_2 between its boundaries (*I* and *II*), their strength σ, length λ and range $2a$ of waves, area of molten metal S_m and its microhardness $HV50$

a new interpretation of the energy pattern of joint formation under the conditions of high-velocity collision of metal plates. Pressure p acting on the near-contact layers of the joint during some time, does certain work on plastic deformation of metal in them. The higher the level of pressure and the longer the duration of its action, the greater is the part of kinetic energy of flyer element W consumed in plastic deformation of the near-weld zone metal (energy W_2), eventually determining the energy balance in the system. However, unlike the very important parameter of the energy group W_2, which even though it is formally related to the conditions of collision and weight characteristics (i.e. thickness of elements being welded), but describes the final results of high-velocity interaction only in the generalized form, the value of deforming pulse I_d is the «bridge» to «microlevel» parameters, as it unites the pressure in the contact zone and time of its interaction with the kinematics and energy of the process, on the one hand, and plastic deformation with the complete running of activation processes in the contact zone and strength of the layer bonding, on the other hand.

The new concepts of deformation-energy and temperature-time conditions of joint formation in explosion welding of metals, developed in the scientific school of VolgSTU, provide a scientifically grounded approach to design of technologies of manufacturing metal laminated composite materials of various configurations.

Physico-chemical features of the processes running in explosion welding, opened up a unique possibility of producing a broad range of composite materials from practically any dissimilar metals and alloys with the adhesion strength of composite layers equivalent to base metal properties. This technology enables manufacturing LCM in the form of sheets, pipes and other structures, reinforced by fibers, as well as composites with intermetallic reinforcement (Figure 10).

Proceeding from the results of investigations performed for a number of Russian and foreign organizations and enterprises, a package of explosion welding technologies has been developed. By the orders of Podolsk S. Ordzhonikidze Mechanical Engineering Plant, Stock-Holding Companies «Kaustik», OJSC «Volgogradneftemash», «Norilsk Nickel» and other organizations, commercial technologies have been developed of cladding by explosion welding large-sized thick-walled billets of bodies and tubesheets of heat exchangers and chemical apparatuses from steels of 22K, 16G2S, 08Kh18N10T grades by LO62-1 brass, VT1-0 titanium, KhN65MV Hastelloy, designed for «Kozloduy» (Bulgaria), «Loviiza-2» (Finland), «Leningradskaya» (RF) NPP and a number of other constructions (Figure 11).

For enterprises of the defense and aerospace complex a number of effective solutions, and a package

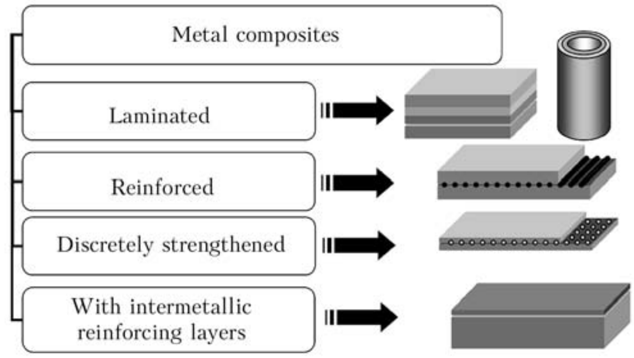

Figure 10. Types of composite materials produced by explosion welding

of fundamentally new combined schematics and technologies have been developed for manufacturing titanium-steel, titanium-magnesium, aluminium-magnesium tubular transition elements of 12–1490 mm diameter of various purposes and configuration. These materials were applied in components of space systems used in «Lunokhod», «Venera», «Mars», «Buran» programs, etc. A technology has been developed of producing composite heat exchangers with inner channels and bulk load-carrying panels from aluminium and titanium alloys for space structures.

Technologies have also been developed for producing composite three- and five-layer titanium-aluminium plates designed for cases of instruments of antenna-feeder devices of space vehicles of «Energiya», «Mir», «Sea Launch», «Buran», ISS systems, etc. (Figure 12). Now all the Russian space systems are fitted with composite components manufactured by this technology.

A unique technology of restoration of cast vanes from steel 30L in guide wheels of hydraulic turbines of 4.5 t weight and about 5 m length each (22 turbines of Volzhskaya HPP have 32 vanes each) by precision local cladding with 08Kh18N10T steel 4 mm thick of three journals on the base of 200–400 mm has been

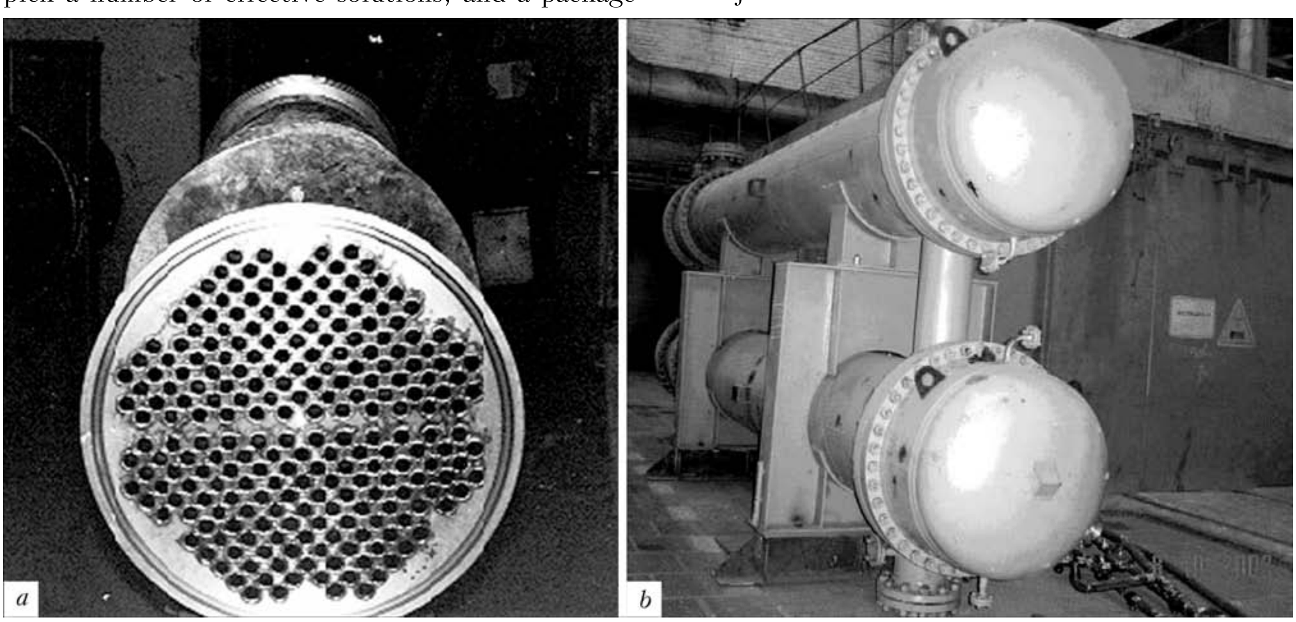

Figure 11. Explosion welded bimetal tubesheet of heat exchanger of «Leningradskaya» NPP (*a*) and bimetal cooler of gas-condensate equipment («Volgogradneftemash», RF) (*b*)

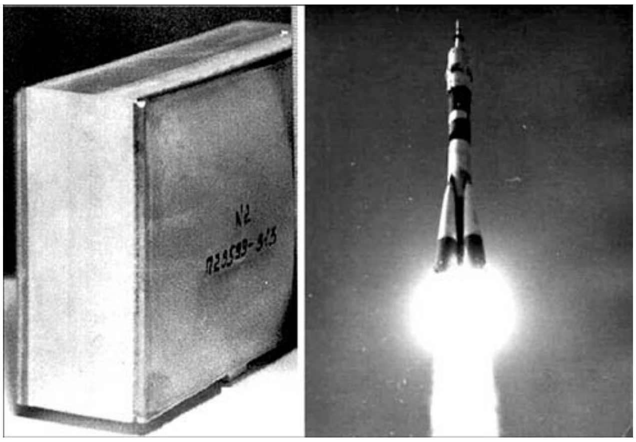

Figure 12. Explosion welded composite titanium-aluminium case of antenna-feeder device of a space system

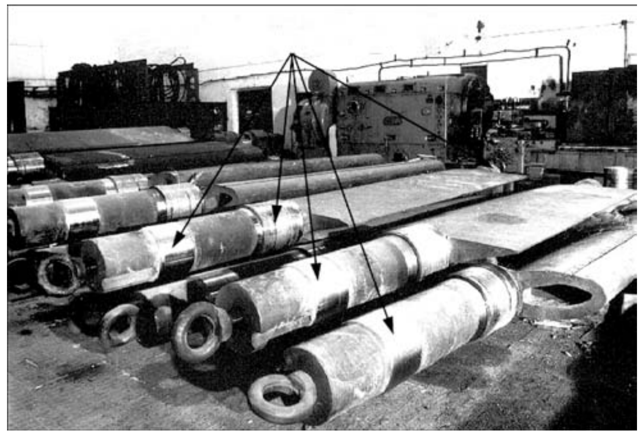

Figure 13. Guide vanes of a hydraulic turbine of Europe's largest Volzhskaya HPP with journals reconditioned by explosion welding after machining (*arrows*)

developed and introduced in Europe's largest Volzhskaya HPP, which was to be repaired after 40 years of service (Figure 13).

Composite materials produced by explosion welding became widely applied in power engineering and electrometallurgy (transition copper-aluminium and steel-aluminium components used for reliable joining of dissimilar sections of electric power circuits), railway transportation (heavy-duty slide bearings with an antifriction layer), metallurgy (bimetal copper-steel water-cooled troughs) and other sectors of the Russian industry.

Cost-effectiveness of introduction of composites produced by explosion welding is due both to saving of expensive and deficit materials, and products acquiring new service properties (improvement of wear resistance, lowering of transient resistance, etc.). In a number of cases, explosion welding is the only technology for producing a number of combinations, composite structures and assemblies.

CONCLUSIONS

1. Analysis of extensive theoretical and experimental material accumulated so far is indicative of the fact that explosion welding is a high-energy process, allowing solid phase production of equivalent joints of similar and dissimilar metals and alloys. The revealed functional correlations between parameters of the studied process and constructed mathematical models enable purpose-oriented control of deformation-energy and temperature-time conditions in the joint zone, thus ensuring formation of the required structure and properties of laminated two- and multilayer composite materials.

2. Owing to a high level of properties of explosion welded composites from dissimilar materials, the latter have found a broad and effective application in different industries (petrochemical, power and aerospace engineering, power generation, metallurgy, etc.), successfully competing with similar products made by alternative processes (surfacing, rolling, spraying, etc.). In a number of cases, explosion welding is the only possible method of producing high-quality metallic composite materials, composite structures and assemblies.

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MONITORING THE FRICTION STIR WELDING PROCESS OF ALUMINUM AND MAGNESIUM ALLOYS

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A three-dimensional modeling of material flow during the friction stir welding process is presented. The model considers both the heat developed when friction takes place between the material and the tool and the plastic deformation developed by its. The dependency between the real thermal field during the welding process appreciated by infrared thermographic control and the quality of welded joints is analyzed. An original on-line monitoring system for FSW using the infrared thermography is described.

Keywords: *FSW, welding parameter, aluminum and magnesium alloys, process modeling, process monitoring, infrared thermography*

The friction stir welding (FSW) process [1], developed recently in the scientific world, has caught the attention of the most important research centers from the entire world as well as of well-known industrial companies from top areas such as airspace or automotive. It can be considered a reference point in the development of joining technologies as well as in the conception and execution of welded joints.

Starting in 2008 welding research using FSW process has been included in ISIM scientific program. ISIM is currently developing a research program regarding complex process modeling, welded joints characterization, developing specific non-destructive examination methods, elaborating a monitoring system and an automatic control of the welding process, studying the performances of new FSW welded structures for top applications.

Nowadays, the research of FSW process concerns the international scientific community from this area as it is proved by the extremely high number of scientific papers (about 800) that were published in main information flow, respectively more then 1800 patents protected in industrial developed countries.

The highest number of scientific papers (~26 %) approaches aspects as properties, performances, testing and quality of welded joints. A special attention is given to FSW process development, welding equipment and tools (~23 %), as well as to the application of FSW process in other materials than aluminum alloys (~16 %). In the same time, the FSW subject is treated by IIW Commision III and by important international conferences all over the world.

Regarding the FSW patents there had been identified about 1800 patents until May 2007. The number of FSW patents is permanently increasing, about 800 patents being recorded between 2004 and 2006.

Welding of aluminum and magnesium alloys. A FSW welding system based on a universal milling machine was developed [2].

Butt welds were done on plates of 4–10 mm thickness made from aluminum Al99.0-EN-AW1200, magnesium alloy AZ31B, respectively from their combination using different welding parameters (rotation speed and welding speed), as well as different shapes and dimensions of welding tools. The welding parameters were modified in the following ranges: rotation speed n = 600–1500 rpm; welding speed v_w = 75–750 mm/min; tool types — cylindrical threaded pin (diameter 4–8 mm for thickness s = 4–8 mm), cone threaded pin (diameter 9/7 mm for thickness s = = 8–10 mm).

For a complex characterization of the quality of FSW joints, an evaluating program was developed as presented in Figure 1 [3].

The welded joints quality evaluation criterion was developed comparing static tensile strength of the base material σ_t^{BM} with the ones of welded joints σ_t^{WJ}. According to the welding parameters that were used in tests, the following values for the $\sigma_t^{WJ}/\sigma_t^{BM}$ ratio were obtained: 0.7–0.91 for Al99.0; 0.50–0.86 for AZ31B. In the case of dissimilar welding of Al99.0 with AZ31B, the ratio between the static tensile strength of the welded joint and the one of Al99.0 was 0.45–0.70.

The optimal welding parameters that determined the maximal values of the static tensile strength are shown in the Table.

Temperature records with a thermographic camera were developed during the experimental program. The experimental set-up allows direction adjusting so that the camera constantly follows the area of ±1 mm at intersection between shoulder and jointing surface on the semicircular side of tool backside, where the temperature is maximal.

The presence of defects (detected by radiographic testing) determined also perturbations of the temperature chart (Figure 2). As consequence the temperature variation in the weld could be used for the monitoring of the weld quality.

Mathematical modeling of FSW material flow. A model was developed for simulating both material flow and thermal field during FSW process considering both the frictional heat developed at the interface

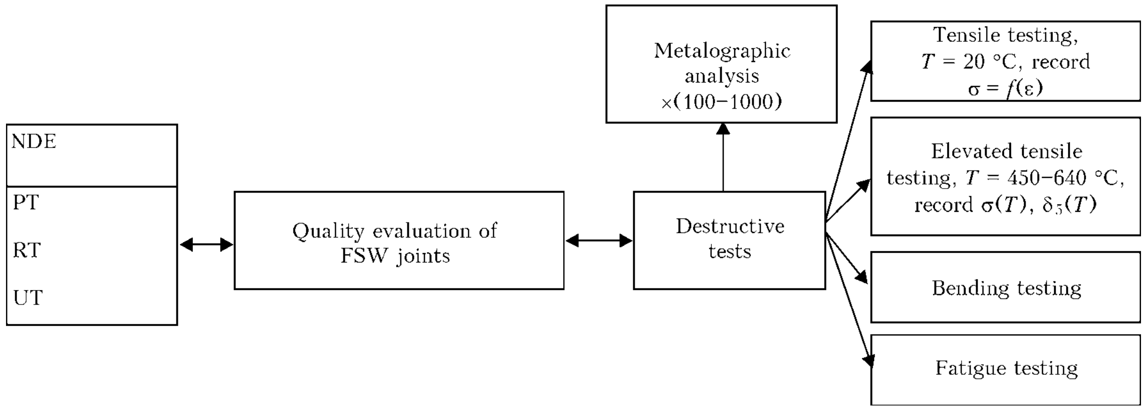

Figure 1. FSW weld quality evaluation program

between the tool and the material and the internal heat generated inside the work piece material due to plastic deformation [4–6]. The model considers the FSW process during its stable phase, known as «welding phase», where all parameters of the process are stable, the tool having a cylindrical pin with no groove or indentation on the shoulder surface.

To simplify the modeling, the rotating tool, around which flow the material that undergoes the plastic deformation and the material that does not suffer any deformation have been considered as fixed borders of the domain.

The entire quantity of heat developed during the FSW process dissipates according to the scheme presented in Figure 3. Simulation conducted on 5754 alloy plates (500 × 210 × 6 mm) revealed the behavior of the material flow, overlapped on the thermal field developed during the welding process. Analyzing the thermal field it can be observed that it is more extent in the advancing side of the tool, because the plasticized material is pushed on this side by the rotational movement of the tool (Figure 4). Focusing on the stream lines, it can be observed that the material from the front of the tool, even from the advancing side of the tool, is forced around the tool pin and pushed in the backside of the tool. The stream lines shows that the moving speed of the particles that flow around the tool pin increases, as the distance to the tool pin decreases. This aspect is a result of two contradictory processes that are interconnected and will play the role of the auto regulation of the heat generating process, similar with that of conventional friction welding.

The first process is that the material particles are drawn in the rotation movement with high speed which generates more heat. The second process is that generating more heat, the material softens, the shear rate decreases and the quantity of heat produced decreases. Beside these, the view from beneath (Figure 4, *b*) reveals that in the same time with the rotation movement, the particles undergo also a vertical movement, the particles plunging towards the bottom of the work pieces surfaces. This movement confirms the presence of a vertex in the welded joint nugget.

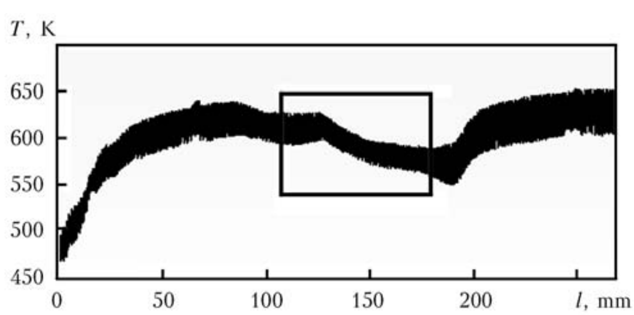

Figure 2. Welding defect detected through radiographic testing and marked on the temperature chart

Monitoring the quality of welded joints. FSW joints quality monitoring was developed using infrared themography. For this purpose a thermo-vision type A40M camera, fixed mounted on the head of welding machine, with specialized software for real time thermographic analysis of image was used. The camera was directed in order to locate the intersection area between welding tool shoulder and joint surface. Al99.5 sheets with a thickness of 10 mm were used for the experiment. The welding was developed with a rotation speed of n = 1500 rpm and a welding speed of v_w = 75 mm/min. It was used a threaded cone tool having the diameter of the shoulder of 21 mm and the diameters of the pins of 9/7 mm.

The experimental program included two categories of artificial defects:

• internal defects situated perpendicular to plates surface covered by subsequent FSW weld; the defects' depth was smaller than the tools' length. There were included cylindrical holes situated at constant steps and having a variable diameter (2–7 mm), elliptic slots of constant length with variable width and depth (b = 2–6 mm) and implants (3 × 4 mm) made by copper, magnesium alloy, tools and stainless steel.

Optimal welding parameters

Materials	Thickness, mm	FSW parameters*		$\sigma_t^{WJ}/\sigma_t^{BM}$
		Rotation speed, rpn	Welding speed, mm/min	
A199.0	5.0	1500	235	0.91
AZ31B	4.0	1180	375	0.86
A199.9 + AZ31B	4.0	1180	190	0.70 (Al)

*Tool geometry — cylindrical threaded pin 6 mm in diameter.

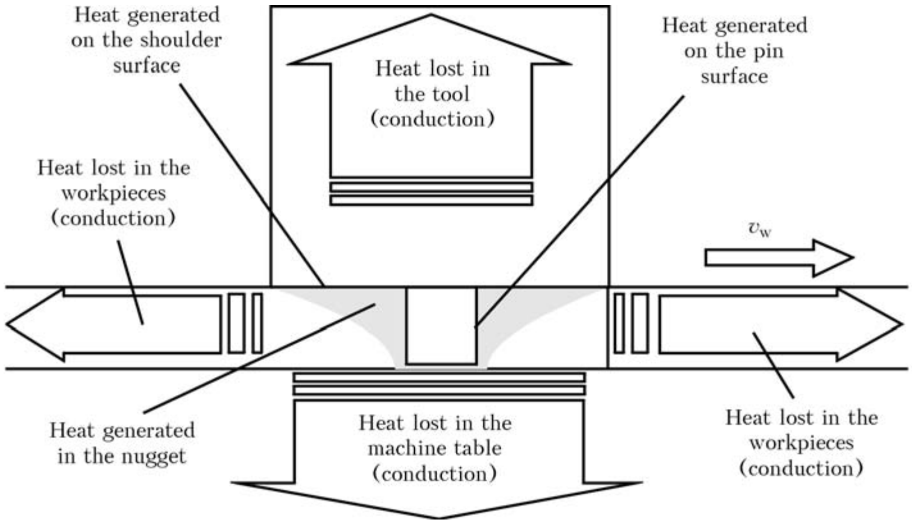

Figure 3. Model of heat generated and dissipated during FSW

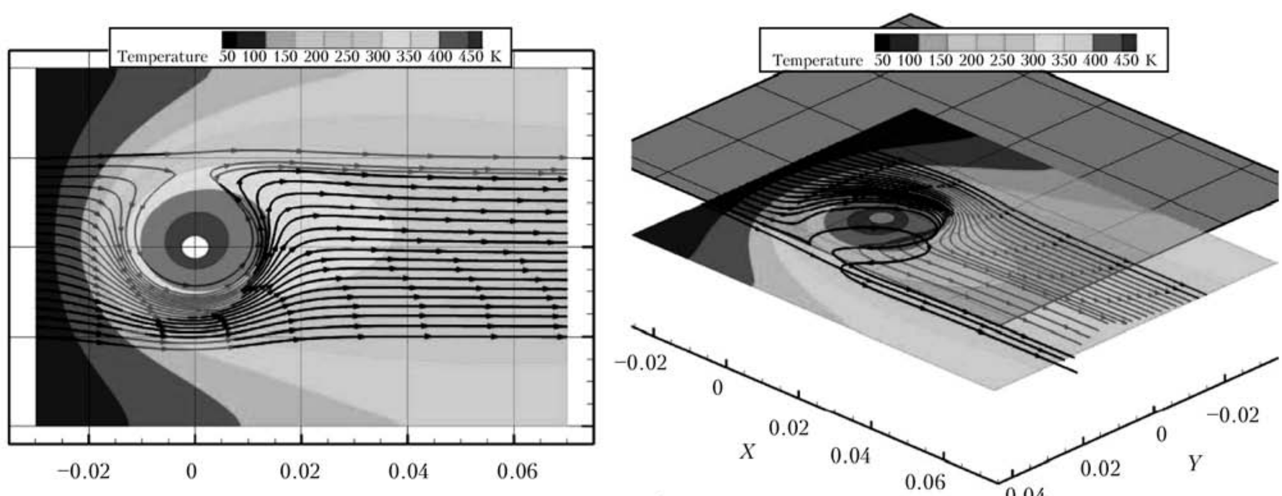

Figure 4. Stream line showing the material flow superimposed over the thermal field: *a* — temperature field and stream lines on the surface of the workpieces; *b* — the same, view from beneath

• defects situated in the frontal axial plane of FSW joint, having variable width and depth (2 × 6 mm) situated on the advancing or retreating side.

Based on the developed research it could be noticed, on one hand, the good results reproducibility considering defects localization and, on the other hand, a dependency between temperature variations and defects dislocated volume. For exemplification, Figure 5 presents the thermographic records obtained in the case of monitoring the defects situated in frontal axial plane on the retreating side. The temperature peaks correspond to the positions of defects along the weld, these positions being marked as bold on the abscissa. The temperature peaks are equally spaced situated, according to the position in which the shoulder of the tool starts to cover the defect.

The temperature variation ΔT, depending on the volume of dislocated defects V is shown in Figure 6; it proves an exponential dependency between the two parameters with a high correlation coefficient.

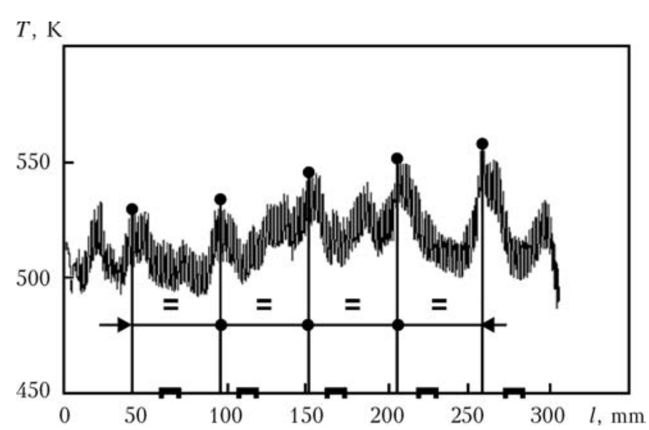

Figure 5. Temperature recording in case of defects situated in frontal axial plane on the retreating side

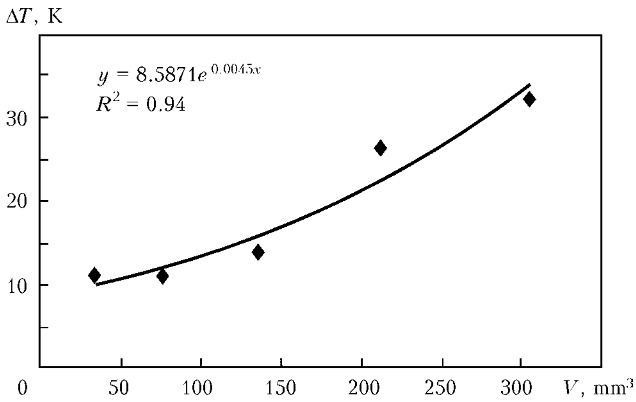

Figure 6. Temperature variation ΔT versus dislocated defects volume V in case of defects situated in frontal axial plane on the retreating side

CONCLUSIONS

Using a FSW system based on an adapted milling machine the optimization of welding parameters for the welding of aluminum Al99.0, magnesium alloy AZ31 as well as the combination of these two materials was done.

The study of material flow during welding revealed that there is a descending movement of material simultaneous with the high rotation speed in which the material from the vicinity of the pin is engaged in. The temperature field is more extended in the part of retreating side of the backside of the tool and the isothermal of high temperature is more extended in front of the tool than in the backside of it.

In order to develop a monitoring system for the FSW process by using infrared thermography experiments with artificial defects have been made. They showed a dependency between the real thermal field measured by on line infrared thermography and the quality of the FSW welds. No matter what shape has the simulated defect, it can be delimited, according to precision limits, a minimum volume needed for obtaining an adequate evaluation of the thermographic records. In fact the experiments have validated the original process monitoring system.

The paper was developed in the frame of CEEX 66/2006–2008 project, with the support of The National Agency for Scientific Research.

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DEVELOPMENT OF AUTOMATIC THERMAL CUTTING PROCESSES IN SHIPBUILDING, METALLURGICAL AND MECHANICAL ENGINEERING ENTERPRISES

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The paper describes investigations in the field of thermal oxygen and plasma cutting of metals conducted at OJSC «VNIIavtogenmash», as well as achievements of this organization and FSUE «TsNIITS» in development and wide industrial application of new generation cutting machines in shipbuilding, metallurgical and mechanical engineering enterprises.

Keywords: *thermal cutting, oxygen cutting, plasma cutting, gas-laser cutting, mathematical model, thermophysical processes, heat-mass transfer, new generation machine, effective applications*

Thermal cutting is the main technological operation of producing blanks for welded structures, and is widely applied in mechanical engineering and shipbuilding, metallurgy and other industrial sectors. In the leading industrial sectors it accounts for 30 % of labour consumption in fabrication of sheet metal structures. In shipbuilding parts from rolled sheets make up 85 % of the weight of ship hull parts. Therefore, the technical level of thermal cutting methods is of decisive importance in ensuring cost-effectiveness of production.

At metal severing three kinds of cutting are mainly used: flame (oxygen), plasma and gas-laser cutting. Oxygen and plasma cutting are the most widely used.

Oxygen cutting allows treating low-carbon steels of different thickness (from 5 up to 2000 mm). Low cost of the equipment, its simplicity ensured a wide application of the process practically in all the spheres of industrial production. However, the technological process of oxygen cutting is characterized by a long time of preheating at the start of cutting and low cutting speed of 0.1–0.7 m/min, this limiting the efficiency, and causing thermal deformations that impair the part accuracy.

Plasma cutting ensures high-speed cutting of steel of up to 30–40 mm thickness, allows cutting other metals, and is accompanied by low thermal deformations. However, the cut surfaces have a noticeable non-perpendicularity and roughness, and plasmatron operation is unstable.

The highest quality of cutting thin metals and nonmetallic materials is provided by gas-laser cutting. It is, however, relatively expensive, and equipment is sophisticated.

Over the last years requirements to thermal cutting in mechanical engineering have changed essentially. A modern thermal cutting machine should be able to treat metal of 1 to 200 mm thickness. None of the existing technologies of thermal cutting (neither oxygen, nor plasma, nor laser), is capable of covering this entire range. Hence the need to develop machines with combined fixtures, in which small thicknesses from 1 to 20 mm will be treated by the plasma process, and those from 20 to 250 mm — by the oxygen process. Requirements of accuracy to the machines have also become higher. A machine should cut out parts to size without allowances for subsequent machining.

In shipbuilding the main requirement to thermal cutting technology is ensuring the accuracy of the cut out blank, in keeping with the requirements of plasma cutting out.

In metallurgy, cutting of metal of 150 to 700 mm thickness is widely applied in addition to cutting sheet rolled stock to size, Here, increase of cutting speed is a problem, as the latter determines the efficiency of the units for continuous severing of steels and scope of the produced rolled stock, respectively.

This paper deals with the aspects of development of theoretical fundamentals of oxygen and plasma cutting of metals, and gives examples of development of high-precision machines for rolled sheet cutting out.

Development of the process of oxygen cutting. In this work in order to find the ways to improve the efficiency of oxygen cutting, an attempt has been made to construct a mathematical model of all the most important stages of the technological process, namely preheating and oxidation of metal, heat transfer, melting and removal of the melt from the cut zone. The methods of three-dimensional mathematical simulation of thermophysical processes and heat-mass transfer in cutting were used for this purpose [1].

The characteristic hydrodynamic features found in oxygen cutting were analyzed by solving the problem of flowing of a viscous heat-conducting medium with a chemically reacting layer. In the general form this problem definition includes the following main equations: equation of continuity, equation of motion, equation of energy, equation of heat input during oxidation, equation of the kinetics of motion or solidification (Stefan's condition).

The above formulated mathematical definition of the problem of heat transfer and melting under the

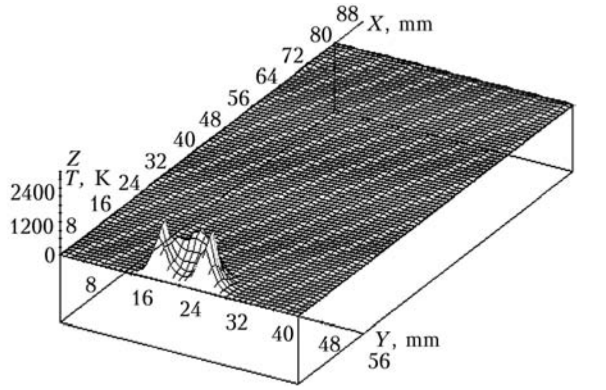

Figure 1. Thermal pattern formed after 1 s under the impact of the preheating flame with outer nozzle diameter of 6.2 mm (T_{max} = = 825 K)

impact of the preheating flame with subsequent oxidation and removal of the melts from the cut zone was solved numerically by the method of finite differences.

Results of computer simulation of thermal pattern development under the impact of preheating flame for the cutter with the diameter of the inner (cutting) nozzle d_{in} = 1.2 mm and outer nozzle diameter d_{out} = = 6.2 mm are given in Figure 1. It is seen from the Figure that the temperature in the subsurface layer (at the depth of 0.5 mm) is distributed highly non-uniformly with a depression along the nozzle axis.

As is seen from Figure 2, active oxidation occurs at first in the area of inner diameter. Conducted computer experiments simulating the process of metal heating by the circumferential preheating flame, revealed the presence of a spatial temperature minimum along the cut axis, which delays the process of the cutting start. The value of temperature depression decreases with reduction of diameter of circular opening for combustible mixture and the flame coming closer to the cut axis.

Kinetics of iron oxidation is the determinant factor for the speed of oxygen cutting of steels.

The process of oxidation at simulation can be presented by the following stages: oxidizer transfer to the solid surface; crystallochemical interaction; new phase formation and growth; oxidizer diffusion through the oxide layer.

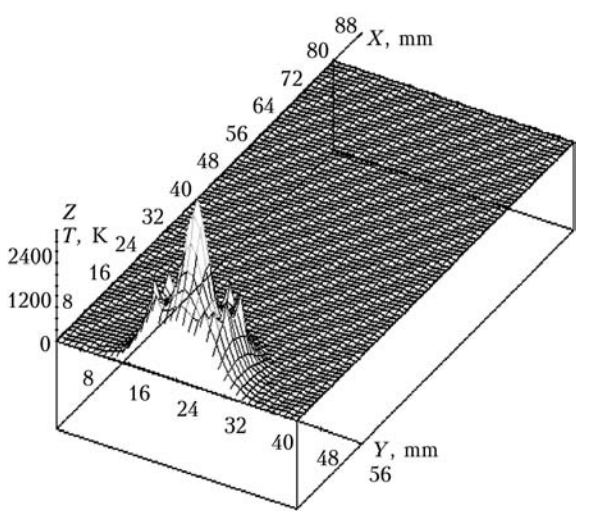

Figure 2. Peak-shaped temperature growth in the cut zone after 5 s (T_{max} = 4742 K)

At T > 1000 K mainly FeO (more than 90 %) is present in the slag melt, so that only the kinetics of wustite formation was considered in calculations.

Let us derive the equation of chemical kinetics of formation and growth of the oxide film based on K. Wagner concepts in the assumption that the oxidation processes can be considered as electrolytic ones, i.e. assuming that the growth of film thickness is caused by diffusion of charged particles (oxygen cations, iron anions and electrons). Let us denote the electrolyte chemical potential as E, number of charged iron ions as N_a number of charged oxygen ions as N_k, and number of electrons as N_y. Then using the Faraday law, oxide formation dm (g/mol) during time dt can be expressed as follows:

$$\frac{dm}{dt} = \frac{R\sigma_0 S}{zF^2}(N_a + N_k)N_e\left(\frac{\partial T}{\partial h}\ln(P) + T\frac{1}{P}\frac{\partial P}{\partial h}\right),$$

where F is the Faraday constant; R is the universal gas constant; T is the temperature; z is the magnitude of ion charge; P is the pressure.

Thus, proceeding from the process mathematical model (on the level of continuum mechanics) we can go over to description of oxide film formation and determination of factors influencing the cutting efficiency. Numerical calculations showed that temperature in the zone of oxide film melting can rise rapidly up to temperatures of metal evaporation (so-called peaking modes). Here microlocal regions are formed, in which melt pressure also increases abruptly, this generating microshock waves (Figure 3), which provoke metal ejection from the depth at which they initiated, which results in an increase of cutting speed.

Figure 4 visually demonstrates lagging of cutting speed across the metal thickness. It is the greater, the thicker the metal. The main factors causing this lagging are the impacts of thermal fields formed allowing for the preheating flame intensifying the oxidation rate in the cut upper part and decreasing heat conductivity at high temperatures of the removed melt in the cut lower part.

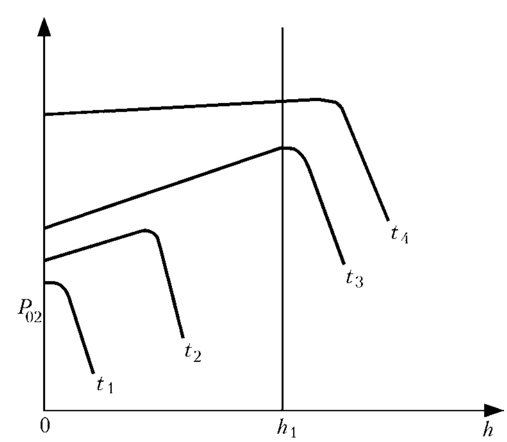

Figure 3. Wave-like nature of pressure propagation from the surface in-depth of oxidized metal

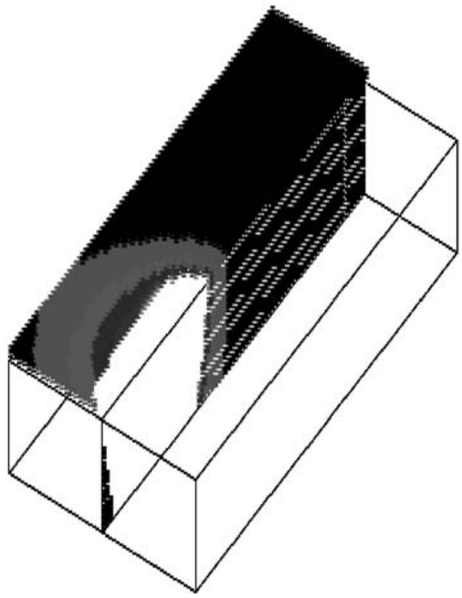

Figure 4. Dynamics of thermal field propagation at formation of a cut in 20 mm thick steel plate

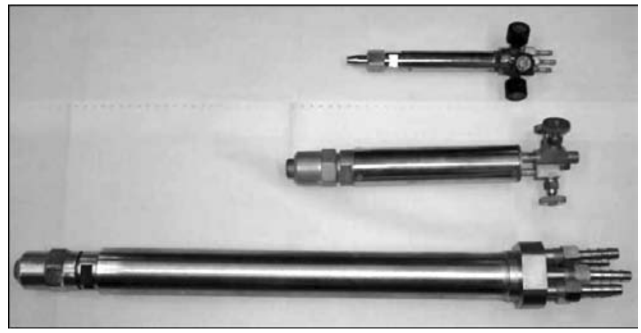

Figure 5. Machine cutters for cutting metal of 150, 300 and 500 mm thickness

In addition, analysis of computer experiments showed that increase of the cutting efficiency can be achieved through application of increased pressure of cutting oxygen, and preheating time can also be reduced due to liquidation of the temperature minimum along the cutter length at metal heating by a circular preheating flame. Based on the results of performed research oxygen cutters with optimum geometrical parameters were developed, in which the angle between the axis of the cutting oxygen nozzle and axes of preheating flame changes depending on the cut metal thickness (Figure 5).

The angle between the axis of cutting oxygen nozzle and axes of the preheating flame was determined proceeding from the condition of contact of cutting oxygen spot and preheating flame spot (bright section) on the metal surface (maximum angle) and from the condition of removal of the above circumferences to the distance of 1.5–2.0 mm (minimum angle). In view of the fact that cutting nozzle diameters and its projection on metal change depending on metal thickness, the following relationships between metal thickness and angles of inclination of preheating flame axes were established:

Metal thickness, mm	5–20	20–50	50–100	100–150
Angle of inclination, deg	15	10	8	5

Angles of cutter inclination are selected so that the heated spot with the maximum temperature was located at the distance of 1–2 mm from the limit of the projection of cutting oxygen jet. The above schematic is implemented in the designs of new cutters of «Nord» series. Figure 5 shows the appearance of cutters for cutting up to 500 mm thick metal introduced at metallurgical enterprises.

Development of the process of plasma cutting of metal. Further development of plasma-arc technologies of metal cutting was performed during investigation of thermal and gashydrodynamic regularities, that showed that the main portion of thermal power applied to the metal is generated by the cutting thermal flow providing metal melting and melt removal by plasma from the cut cavity. During cutting part of the heat propagates into the cut metal mass adjacent to the cut, and part of the melt is ousted to the side surfaces of the cut. At radiation of an open arc column and that with a plasma plume some of the heat is lost in the plasmatron.

It is established that the speed of metal cutting depends on the thickness of the melt front film which becomes greater when moving deeper into the cut cavity, this leading to «lagging» of the cutting jet in plasma-arc cutting, limiting the cutting speed and distorting the cut out contour. Lagging can be reduced by cutting by an arc with a high current density, plasma jet speed and rational selection of plasma media. It is important to ensure the maximum uniformity of heat transfer from the cutting arc to the front of the cut metal through the thickness of the object being cut. This is also essential for reducing the non-parallelism of the cut surface, characteristic for plasma-arc cutting.

As the most uniform width of the cut is achieved in the zone of the spot slipping, in order to obtain the highest quality (parallel) cut surfaces at cutting, it is important to take measures ensuring maximum spreading by depth of the scanning zone of the anode spot, and applying cutting current sources with steeply-falling volt-ampere characteristics providing constant current at variations of the length of the scanning cutting arc. As the energy applied by the cutting flow will only ensure formation of the cut, the cut should have a minimum width, sufficient for removal of the formed melt through it and preventing filling of the obtained through-thickness cavity by molten metal.

It is established that the volumes of the melt removed to the side surfaces of the cut, decrease at high speeds of its removal, and the melt solidifying on the cut surfaces, forms a cast layer and roughness. A reduction of the cast layer depth and roughness can be achieved by intensive removal of the melt from the formed cut cavity by the high-speed plasma flow. Intensity of melt removal increases with the «rigidity» of the cutting arc determined by the composition, density and mass flow of plasma, which is achieved by limitation of current, gas flow rate, length of the cutting nozzle channel and reduction of its diameter. The latter at high current densities requires stability of their value both during excitation of the cutting arc, and at fluctuations of the mains voltage of the arc power source and arc length during cutting. For stable operation of the plasmatron under these conditions and prevention of development of an emergency «double arc» condition, fundamentally new types of current sources powering the cutting arc were developed. They are fitted with microprocessor stabilizing devices which provide a stable maximum energy density and allow achieving a high speed of the plasma jet, this promoting an increase of the cutting speed, resistance of the hafnium cathode, reduction of non-parallelism of the cut surfaces. Application of these sources allowed a one and a half times increase of the cutting speed, doubling the resistance of the hafnium cathode, reducing the non-perpendicularity and roughness of the cut surfaces.

New UPR4011 units developed by «Spektr Plus» Company (St.-Petersburg) allow cutting metal 2–100 mm thick and are installed on modern plasma cutting machines.

During investigations also different kinds of plasma media were determined, the application of which will be rational: in addition to compressed air for preliminary cutting of metals, it is also rational to apply oxygen for finish cutting of steels, and plasma of a rich mixture of oxygen with nitrogen for their high-speed cutting; nitrogen or its mixtures with hydrogen for alloyed steels and copper, and argon-hydrogen mixture for finish cutting of aluminium.

Development and introduction of new machines for thermal cutting by VNIIavtogenmash. VNIIavtogenmash developed the concept of accelerated upgrading of the available fleet of thermal cutting machines (TCM). At the first stage upgrading of the available machine fleet is performed. For this purpose the condition of the old machine is examined, on the basis of which the project of its upgrading is developed. In the maximum variant replacement of obsolete NC devices, electric drives, mechanical modules, cutting fixtures is performed under the conditions of operating production. All the elements newly established in the machine (cutting device and kinematic part of the machine) are made taking into account the performed range of investigations and are on the world level.

The main factor of improvement of TCM technical level is application of the newest control systems based on industrial computer stations. A complete system based on universal NC 4C 300 FAST controls not less that 4 coordinates, has a control panel based on an industrial computer with 14" colour display, built-in magnetic disc storage and photo scanning device. The system can provide reversal and resuming of cutter motion around the contour with restoration of the technology and interference elimination. Connection to personal computer and other devices, monitoring the tracking errors, storage, debugging of control programs, etc., is also possible. System cost is relatively low.

Foreign control systems of «Berni», USA, were also used for upgrading. Principal upgrading resulted in enhancement of the functional capabilities of wide-gantry «Omnimat» machines in OJSCs «Kolomensky Zavod», «Yuzhuralmash» and other enterprises. In particular, there is the capability of assigning from the operator panel the programs for cutting more than 50 typical parts. By their precision characteristics, they are two times and by their efficiency — by 30 % superior to the old machines. On the other hand, compared to machine replacement by new ones, upgrading allows 2–3 times reduction of the capital expenditures for restoration and improvement of blanking production. Altogether, more than 500 machines with program control both for oxygen and plasma cutting were upgraded. All this confirms the progressiveness and effectiveness of the elaborated approach to solution of this problem and rationality of its wide acceptance as an effective means of development and raising of the engineering level of machine thermal cutting. Upgrading activities are currently carried on at a rapid pace. Term of upgrading one machine is equal to 3 months on average.

The second stage is development of new TCM. The following was developed for designing high-precision machines: dynamic model of motion errors of the mechanical drive and gantry machine structure, which was the basis for proposing the procedure of calculation of the errors of cutter motion, allowing for the most important components of deviations from the specified path [2]. Equations were derived for determination of the cutting speed on the linear and curvilinear sections, depending on the set dynamic accuracy of the mobile elements, cyclic components, drive kinematic errors, gantry weight and contour curvature. Solutions were proposed for lowering the kinematic and dynamic errors of machine elements.

Proceeding from the work results, a new typesize series of machines of a higher accuracy and efficiency was designed, and new generation gantry TCM were developed and their batch-production was organized. Based on the results of the conducted investigations, VNIIavtogenmash developed, tested and introduced a basic model of new generation «Almaz» machine (Figure 6) with the tracking accuracy not lower than ±0.2 mm and photocopying gantry-cantilever «Luch» machine for oxygen cutting (Figure 7). By customer requirement the machine is fitted with new cutting devices for: high speed oxygen cutting of 6 to 150 mm thick steel; cutting thin metal of 2 to 6 mm thickness; cutting 100 to 500 mm thick metal.

New generation machines developed by FSUE «TsNIITS». One of the main directions of activity of TsNIITS is development and manufacturing of NC TCM. More than 1000 machines for plasma and oxygen cutting of «Kristall», «Granta» type developed at the Institute and produced in 1970–1990s were suc-

Figure 6. Gantry TCM with two oxygen cutters and one plasma cutter

cessfully introduced in the enterprises of Russia and CIS countries [3].

TsNIITS marked the start of the new century by development and establishing production of new generation machines of «Ritm-M» type. These machines have an essentially higher accuracy of part cutting owing to application of modern drive sets, microprocessor-controlled plasma cutting sources, new generation industrial computers and software, and enhanced technological capabilities as a result of fitting them by marking and laying modules.

Let us consider the main modifications of machines developed by FSUE TsNIITS, as well as the most interesting solutions implemented in their design.

In 2001 TsNIITS designed, manufactured and introduced in the sheet-rolling shop #3 of OJSC «Severstal» four wide-gantry TCM of «Ritm-5000» type (Figure 8). Machines fitted with two driving carriages were designed for contouring the edges of sheets fed from the rolling mill. Three machines were made in the plasma variant, and one in the gas variant. Special requirements made of the machines, include three-shift operating mode in the shops of metal-working enterprise and 5 m maximum width of the treated sheet.

To accelerate the process of TCM design and manufacturing, as well as lower their cost, development of

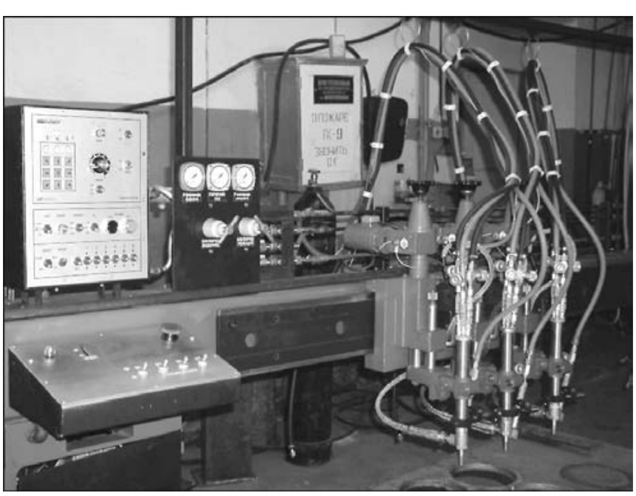

Figure 7. Gantry-console TCM with three oxygen cutters

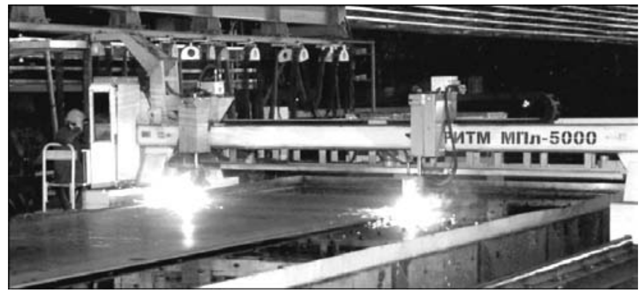

Figure 8. Wide-gantry TCM of «Ritm-MPl-5000» type with two plasma carriages for cutting up to 5 m wide sheets

the module series of TCM building blocks was started in 2003. Development was completed by producing the prototype model of «Ritm-M» machine (Figure 9). Plasma variant of the machine was manufactured and introduced in the machine-building plant in the city of Ussurijsk. Continuation of the work on development of modular building blocks in 2004–2005 led to development and manufacturing of three-cutter gas bock designed for cutting rolled sheets with simultaneous edge beveling for welding. Three-cutter blocks were installed in machines made by the orders of FSUE «Admiraltejskie Verfi» and Lavochkin SEA.

In 2006–2007 development of the typesize line of light-weight and relatively inexpensive TCM of both the gantry and console type for cutting out rolled sheets of a small width, was performed. Combined gantry TCM with one-sided drive «Ritm-MA PPlKP-2.0» for cutting up to 2 m wide sheets was manufactured by the order of OJSC «Aliter-Aksi» (St.-Petersburg) (Figure 10). Combined console TCM with one-sided drive «Ritm-MK PkPlKP-1.5» for cutting up to 1.5 m sheets was supplied to AMT Ltd., Nizhny Novgorod.

In 2007 a system and sensor for monitoring the initial mounting of plasma cutters in the plasma module and gas cutting module with a reduced flow rate of the combustible gas and cutting oxygen were developed. All the TCM of «Ritm-M» type produced by FSUE TsNIITS are now fitted with these module units.

The following of the original engineering solutions implemented in TCM, should be noted:

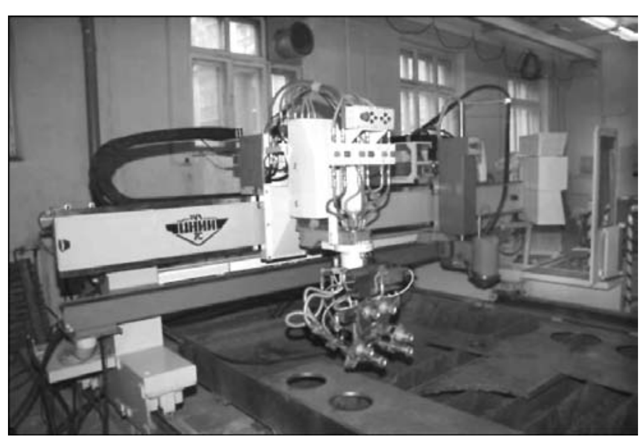

Figure 9. Combined TCM fitted with a plasma module and three-cutter gas assembly with up to 2.5 m width of treated sheets

Figure 10. Combined gantry TCM with one-sided drive and up to 2 m width of the treated sheet

- automatic system of stabilization of the cutting position above the part surface (Figure 11);
- system of determination of the coordinates of metal sheet edges (Figure 12);
- device for remote ignition of gas cutters;
- operating tool for implementation of the technology of water-injection plasma cutting under the water curtain (Figure 13);
- stabilizer of SVR-3M cutter height, made using single-turn eddy current sensor of cut position and protected by a patent;
- «Adapt» system of TCM adaptation to sheet position on the cutting table with automatic positioning of the tool in the cut starting point, which has no analogs in the local industry or abroad.

«Adapt» system on the basis of a stabilizer of SVR-3M cutter height with a single-turn eddy current sensor and appropriate software is capable of:

- maintaining the specified working gap between the nozzle of the gas or hood of the plasma cutter and metal sheet being cut, which is distorted;
- preventing emergency lowering of the cutting assembly right up to hitting the metal sheet being cut as it approaches the sheet edge or at falling of the cut out part beyond the sheet plane;
- preventing breaking up of the cutting assembly by emergency switching off of its motion at riding over the overturned cut-out parts or fragments of the cut-up sheet deformed by heating;
- determining the co-ordinates of the metal sheet edges before its cutting for entering these data into the controlling computational complex to achieve the optimum placing of the cutting chart on the sheet taking random position on the cutting table, and automatic moving of the cutting assembly into the starting point of the cut.

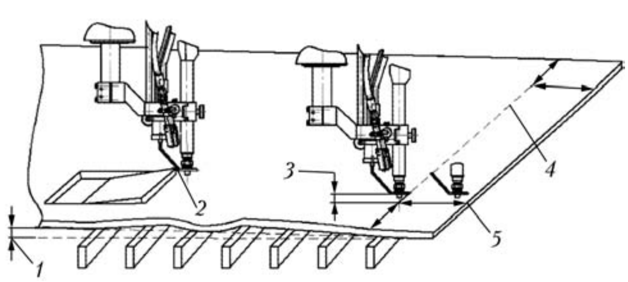

Figure 11. Functions of «Adapt» system: *1* — determination of sheet position skewing angle; *2* — sending a signal about antenna contact with an obstacle; *3* — working gap stabilization; *4* — program of sheet edge scanning; *5* — sending a signal about antenna crossing the sheet edge

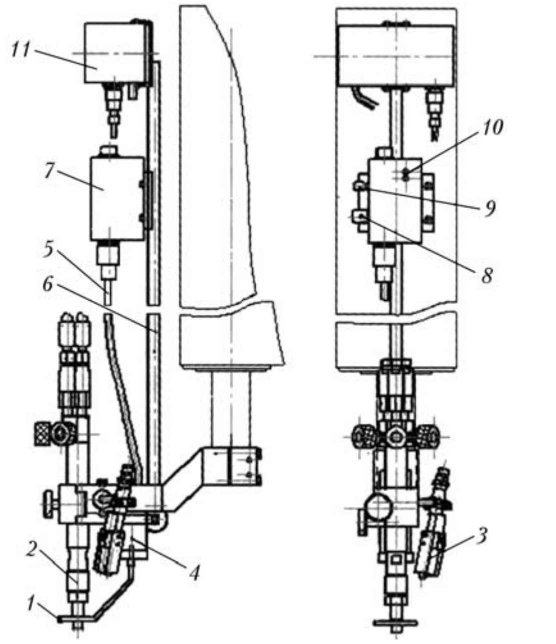

Figure 12. Schematic of arrangement of SVR-3M and UPG-2 devices on TCM carriage: *1* — single-turn antenna of height stabilizer; *2* — gas cutter; *3* — lighter; *4* — case of height stabilizer sensor; *5* — height stabilizer connecting cable; *6* — rod-holder; *7* — electronic block of height stabilization; *8* — knob of smooth height setting; *9* — knob of step-like height setting; *10* — signal light-emitting diodes; *11* — electronic block of gas ignition

Three engineering solutions formalized as TsNIITS inventions were used in development of SVR-3M and «Adapt» system. The first is related to a device of sensor cooling by compressed dry air, which comes to the casing of electronic block for signal treatment, and through the openings in sensor holders is fed to

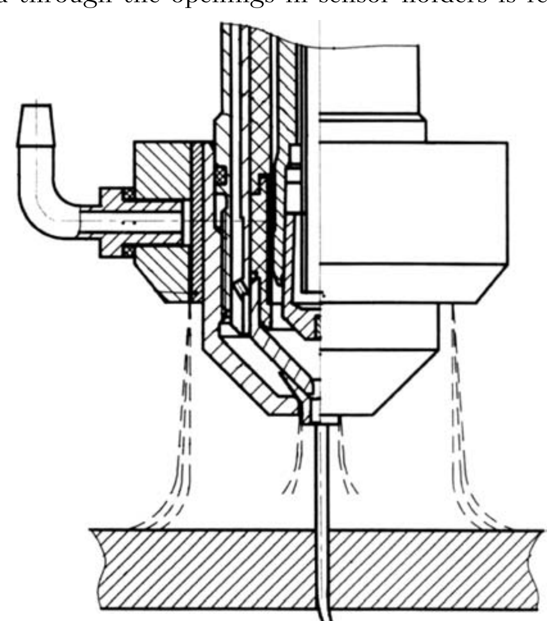

Figure 13. Schematic of operating tool for water-injection plasma cutting under a water curtain

the antenna of eddy current transducer; second consists in a galvanic decoupling between the sensor antenna and electronic measuring circuit, which allowed applying to the antenna DC pilot voltage relative to the earthed metal sheet. Due to that a relay circuit operates at antenna collision with an obstacle in the form of an overturned cutout part or sheet fragment deformed by heating, and the machine stops, preventing breaking up of the cutting assembly. The third solution involves application of SVR-3M for determination of coordinates of metal sheet edges for adaptation of the program of motion of thermal cutting machine tool to the specified position of the sheet on the cutting table. Its essence consists in displacement of a carriage which accommodates the processing tool and eddy current sensor of the tool height regulator located above the sheet, along the sheet surface to its edge with the switched on height regulator. As the carriage with the sensor approaches the sheet edge, the edge effect is manifested: a fast change of the signal at the sensor output at its displacement into the region of the sheet edge, which results from the influence on the sensor of the space beyond the edge, which is perceived by the sensor as an increase of the distance to sheet surface.

In 2006 specialists of the Institute performed additional investigations on application of water injection plasma cutting under a water curtain on new «Ritm-M» and «Alfa-M» machines. For this purpose they were fitted with a new generation plasma module, incorporating a special water-injection plasmatron for metal cutting under a water curtain. The attachment, enclosing the plasmatron hood, is used to create the water curtain. The water is fed into the attachment along a hose through a nipple, and flowing out through a 0.2 mm wide slot, creates the water curtain. When the plasmatron is used for water-injection plasma cutting, an additional outer nozzle with grooves is applied. This nozzle is mounted coaxially with the inner nozzle and is pressed up by the hood. Water is fed (0.25–0.35 l/min) to the nozzle channel and into the arc zone from the cutter cooling system along the grooves of the outer nozzle located on the inner and outer surfaces. This water partially evaporates, partially dissociates into hydrogen and oxygen creating a neutralizing atmosphere in the arc zone, which reduces sheet edge saturation by oxygen; 0.06–0.10 l/min of water penetrates into the nozzle channel (water flow rate is determined by plasmatron design).

Testing of the developed assembly of water-injection plasmatron with an attachment to create an air-water curtain on the thermal cutting machine showed the following. After excitation of the cutting arc and cutting start, water and compressed air were switched on, which were fed into the attachment creating a shield around the plasma arc. Cutting through the metal sheet, the plasma column ran into the water. Fume, dust and aerosol evolution was essentially reduced owing to their absorption by water, which led to the conclusion of the good prospects for application of the technology of water-injection plasma cutting under an air-water curtain in the new machines manufactured by FSUE TsNIITS.

Software for thermal cutting machines developed by TsNIITS is based on a multitasking operating system QNX6 of a rigid real time and Photon graphic shell. In terms of structural organization the software in the comprehensive form is a set of the following program subsystems interacting with each other:

- operator interface;
- motion control subsystems;
- technology control subsystems;
- manual mode control subsystems;
- automatic mode control subsystems;
- subsystems of preparation of frames of the controlling program (CP).

Synchronizing and coordination of subsystem operation is performed through system mechanisms of priority scheduling, exchange of opinions, common storage areas, and program timers. Time cycle of program control, depending on the tasks solved by the subsystems, varies from units of milliseconds (motion control subsystem) up to several tens of milliseconds (operator interface module).

CP is set up for a specific machine configuration using the conditional translation commands, which optimizes the code received by the program both by size and by speed. CP has the following features:

- compactness (total volume of the system and applied part does not exceed 10 Mb);
- realization of the entire spectrum of control system functions by program means in one processor using relatively simple and inexpensive signal input–output boards;
- a large set of program tuning constants for fine adjustment of control system parameters, taking into account all the fine points of the technological process of plasma and gas cutting;
- support of automatic positioning of the cutters at the operational height above the sheet, height control during notching, height stabilization during cutting, cutter lifting at idle runs;
- control of a smooth increase of cutting oxygen flow during notching, supporting different modes of CP fulfillment (cutting, tracing, contouring, simulation, continuous, frame-by-frame, cyclic), as well as reverse motion along the contour and return to the contour;
- possibility of immediately changing the machine motion speed, cutter height above the sheet, technological retention intervals in all the operating modes;
- ability of monitoring in the screen the cutter motion around the contour in «Magnifying glass» mode with up to 10 fold magnification factor, which is particularly urgent for complex cutting charts with a large number of parts;
- convenient service for diagnostics and setting up (including the ability of viewing the graphs of mismatch variation in real time, viewing the signal state

tables with indication of mnemonic symbols for each of the signals);

• support of CP entering from the keyboard, diskette, USB flash-memory and through Ethernet communications channel;

• organizing CP file storage in the form of a scalable system of embedded folders;

• supporting parametric CP, including the ability of the user compiling their own parametric programs for commonly encountered part configurations;

• subprogram support;

• capability of geometric transformations of CP contour incorporated in display image storage (scaling, turning to a specified angle, mirror reflection relative to coordinate axes, referencing to sheet position);

• calculation of equidistant contour for the cut width correction entered from the operator panel;

• capability of interrupting CP fulfillment in an arbitrary point and capability of resuming cutting from the stopping point also after complete switching off/on of machine power;

• access to control system functions through embedded user menus and hot keys, built-in help for each of the menu items.

In conclusion, it should be noted that FSUE TsNIITS is working continuously on improvement of thermal cutting machines. One of the most recent developments of the Institute is laser TCM adapted to the conditions of ship-building enterprises. It was created using 5 kW ytterbium fiber laser YLR-5000 of IPG Corporation based on «Ritm-5» machine. OJSC VNIIavtogenmash is developing a machine for cutting up to 700 mm thick metal by the method of oxygen-flux cutting for metallurgical enterprises.

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TECHNOLOGY AND EQUIPMENT FOR FLASH-BUTT WELDING OF HIGH-STRENGTH RAILS

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The problems of weldability of heat-hardened rails of modern production using the flash-butt welding method, development of technologies and equipment for their joining have been considered. It was shown that some uncontrollable impurities in rail steels deteriorate their weldability. The technology and equipment for welding of heat-hardened rails have been developed, providing the mechanical properties of welded joints on required standards.

Keywords: *flash-butt welding, heat-hardened rails, bend tests, non-metallic inclusions, microstructure of heat-affected zone, fracture surface*

The freight traffic density of railways in the industrialized countries is continuously growing. The service life of rails amounts no longer to decades, as it was in previous century, but to years. At some sections of Syberia and Donbass railways the rail replacement is performed each 4–5 years. In connection with the initiation of fatigue defects in the rails the volume of repair works on restoration of integrity of in-service railways has been increased [1].

In the last decade the application of heat-hardened rails, which allow increasing the life and reliability of railways, has been considerably increased. In CIS countries more than 70 % of rail rolled stock is applied for heat-hardened rails. The application of heat-hardened rails became essentially wider in the European countries, USA and China.

The main manufacturers of heat-hardened rails in CIS countries [2] are Nizhnetagilsk (NTMW) and Novokuznetsk (NKMW) Metallurgical Works, which produce all types of rails used for the heavy-loaded railways. «Azovstal» Works produces rails in smaller amounts and a part of them is subjected to volume heat hardening.

During the lay out of seamless tracks, and also in their repair the rails are welded into long sections. Welding is performed mainly (more than 90 %) by using the flash-butt method, thus practically providing for the equal strength of welded joints with the base metal, including also the fatigue test characteristics.

The E.O. Paton Electric Welding Institute has a many-year experience in the integrated development of technologies and equipment for the flash-butt welding; alongside with the development of welding technologies, the systems of automatic control of the process, power supply sources, equipment for welding and accompanying operations, in particular for flash removal, are developed. In the last decades this approach allowed the creation of number of generations of flash-butt welding equipment, which have no analogies in the world practice. It is based on the continuous flashing welding technology with a programmed change in main parameters [3]. The application of this technology considerably improved the process power characteristics and increased its efficiency and quality of welded joints. The flash-butt welding was for the first time applied in the field conditions during the laying out of seamless tracks and also in their repair. The E.O. Paton Electric Welding Institute is working many years in a close cooperation with Kakhovka Plant of Electric Welding Equipment (KPEWE), which mastered the serial production of flash-butt welding equipment by the developments of the Institute.

Over the last five years the rail welding enterprises began to use the heat-hardened rails. It was found that in welding at the basic conditions their static bend test characteristics are lower than standard ones. In this connection the integrated research of specifics of heat-hardened rail joints formation was carried out at the E.O. Paton Electric Welding Institute by the task of the Ministry of Rail Roads of Ukraine and Russia to define the causes of deterioration of weldability and to improve the welding technology.

The batches of heat-hardened rails R65, produced in 2004–2006 at «Azovstal» Works (steel M76), NTMW (steel E76F) and NKMW (steel K76T), were welded. The welding of heat-hardened rails U75V, produced in China, was also performed for comparison. The chemical composition and mechanical properties of rail steels are given in Tables 1 and 2 [2].

The welding was performed using updated welding machines K1000, K920, K922, serially-produced at KPEWE. The tests were carried out according to the procedure accepted at the rail welding enterprises of Ukraine and Russia [4]. The representatives of All-Russian Research Institute of Railway Transport participated in this operation.

The metallographic examinations of welded joints were performed in the laboratories of the E.O. Paton Electric Welding Institute. The analysis of microstructure of fracture surfaces was carried out in the scanning electron microscope JSM-840 with microanalyzer Lynk-Systems, and the chemical composition of structure components was examined in the Cameca microanalyzer SX-50 (France).

Table 1. Chemical composition (wt.%) of steel of rails R65 (GOST R 51685–2000)

Grade of steel	C	Mn	Si	P	S	V	Ti	Al	Cu
M76	0.71–0.82	0.75–1.05	0.25–0.45	< 0.035	< 0.040	–	–	0.02	–
E76T (pilot batch)				< 0.030	< 0.035		0.007–0.025		Up to 0.15
K76T (pilot batch)									
E76F				< 0.025	< 0.030	0.03–0.15	–		
K76F									
U75V	0.70–0.78	0.70–1.05	0.50–0.70	< 0.035	< 0.035	0.04–0.08	–	–	–

Table 2. Mechanical properties of batches of rails R65 of steel M76, K76F, E76F, U75V

Grade of steel	Hardness *HV*4.9	Tensile strength σ_t, MPa	Yield strength σ_y, MPa	Elongation δ, %	Reduction in area ψ, %	Impact toughness a_n, MJ/m^2
M76	280–320	800–1100	500–700	≥ 6.0	≥ 20.0	≥ 0.5
K76T (pilot batch)	340–390	1180	800	8.0	25.0	
E76F						

Table 3. Main condition parameters of welding batches of rails of steel M76, K76T, E76F, U75V

Welding condition	Time of welding t, s	Tolerance, mm, per		Upsetting force P, kN	Maximum specific power, kW/mm^2
		flashing L_{flash}	upsetting L_{upset}		
CF*	180–230	45–55	12–13	450	0.002
PF**	65–80	15		600	0.035

*Basic technology (continuous flashing).
**Improved technology with a pulse flashing.

At the first stage the welding of rails, listed in Table 1, was performed at the basic conditions (mode CF), accepted for the standard rails (Table 3). The change in basic condition parameters during the process of welding is shown in Figure 1, *a*. The accepted welding conditions provided for the equal heat input and deformation in welding of all rail batches.

The results of static bend tests of rail joints are given in Table 4, where the standard values, to which the test results should correspond, are indicated. In comparison of the given data it is seen that in the rail batches of steel E76F and K76T the average values of deflection f_{defl} and fracture load P_{bend} are below the admissible level, whereas in the batches of steel M76 they are in compliance with the standard requirements. The results of dynamic bend tests of rails of steel U75V are also below the standard values.

The fracture of joints of all rails during the static and impact bend tests occurred along the joint line, where the deterioration of hardness and strength of

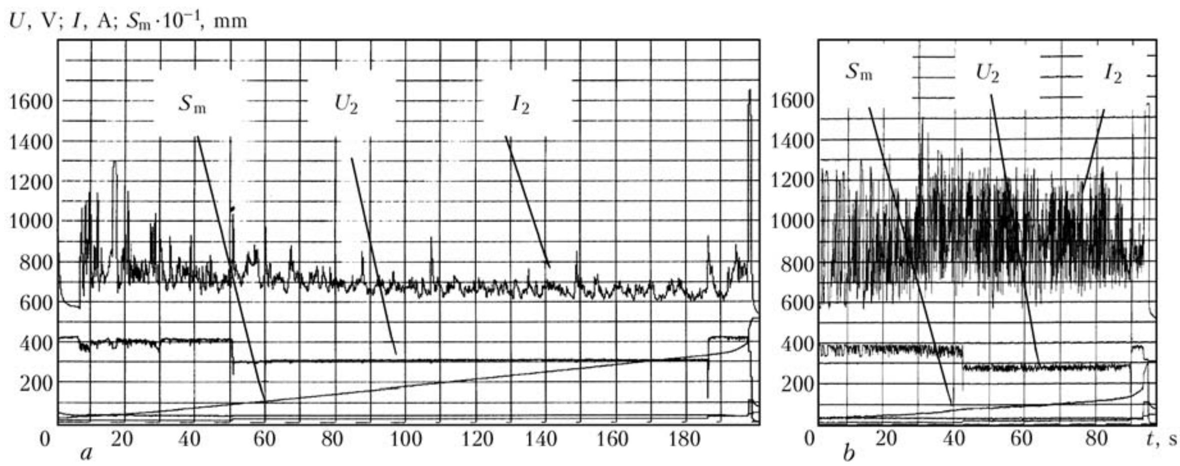

Figure 1. Change in main welding condition parameters (voltage U_2, current I_2 and movement of a mobile column S_m) in welding of rails R54 using the machine K1000 at the CF (*a*) and PF (*b*) mode (see Table 3)

Table 4. Results of static bent tests of joints of batches of rails R65 of steel M76, K76F, E76F, U75V

Grade of steel	Mode CF			Mode PF			Standard values (not less than)		
	P_{bend}, kN	f_{defl}, mm	A, kJ	P_{bend}, kN	f_{defl}, mm	A, kJ	P_{bend}, kN	f_{defl}, mm	A, kJ
M76	1800–2400 / 2050	30–80 / 35	–	1800–2300 / 2250	35–60 / 40	–	180	30	–
K76T	1800–2500 / 2100	12–35 / 19		2300–2700 / 2350	30–60 / 32				
E76F	1800–2500 / 2100	12–40 / 21		2300–2700 / 2350	32–60 / 34				
U75V	1600–2100 / 1800	25–60 / 34	25–60 / 29.4	1550–2200 / 1850	25–60 / 32	49–98 / 78.4	150	22	49

Note. A — fracture energy.

metal was observed (Figure 2). The heat-affected zone (HAZ) of joints of rails of all batches had the equal width and structure, typical of the flash-butt welding, because the rails were welded at the similar heat input. For the joint line metal a coarse-grained sorbite structure is typical (Figure 3). The point of primary austenite grains, fringed by ferrite precipitations, was 3–4. The size of grains decreased as it moved away from the joint line, the sorbite structure preserved itself.

It was established through the metallographic examinations of rails joints and fractographic examinations of fractures of welded specimen that reduction in strength values of rail joints of the mentioned batches was due to the formation of 2D oxide structure components in the weld zone. It is clearly visible in the rail joints of steels E76F and K76T. In the rail specimens of steel M76 such oxide structure components were not revealed, however the globular inclusions of iron and manganese oxysulfides as well as iron silicates were revealed.

The Figure 4 demonstrates the fragment of the fracture of rail joints of steel E76F after the tests. On the surface of fractures two groups of defects can be distinguished: group A — at the areas, where crystalline fracture is absent; group B — at the areas, where there is a fine-crystalline fracture, characterized by its grey or dull shade. In flash-butt welding practice they are called dull spots (DS).

When analyzing the microstructure of fracture surface of mentioned defects it was established (Figure 5, *a*) that defects of group A represent the monolithic oxide film, the base of which consists of iron silicates. Its composition includes also the oxides of active elements contained in the mentioned rail steel (titanium, aluminium, vanadium). The metallic bond at this area is absent. The thickness of oxide films is 20–100 μm.

In the DS microstructure (Figure 5, *b*) alongside with the oxide films, thinned to 10 μm (area *1*), the areas of transcrystalline fracture (area *2*) are available, whose structure is similar to that of fracture areas on the base metal (Figure 5, *c*). Thus, DS represent themselves as the areas with a dispersed thin oxide film.

During the rupture tests of standard specimens, where the DS area is up to 90 % of the specimen area, the strength characteristics are close to those of the base metal. At the same time the strength values at the bend tests are only 10–20 % of those of the base metal.

The Table 5 presents the results of X-ray diffraction microanalysis of chemical composition of oxide inclusions revealed in fractures of rail joints after the bend tests. As is seen from the Table, the monolithic oxide films in the rail joints of a single batch have a chemical composition close to the fragments of oxide film in DS.

In the fractures of joints of rails of steel M76 the globular inclusions of iron and manganese oxysulfides as well as iron silicates are present. In the composition of oxide films of joints of rails of steel K67T the increased content of calcium and titanium is revealed, besides the iron silicates, and aluminium and vanadium is revealed in the steel E76F rail joints. Here, their content is much higher than in the rail steel (see Table 1).

All batches of rails were welded at the same conditions. The formation of oxide films in the metal of welds, made on the rails of steel K67T, E76F and U75V, gives grounds to consider that this is connected with the presence of titanium and vanadium in their composition, on the contrary from the rails of steel M76, having no oxide films in the joints.

The presence of oxide films is the main reason of instability of values of f_{defl} and P_{bend} in the rail batches of steels E76F, K76T and U75V at the bend tests. The minimum values of characteristics correspond to

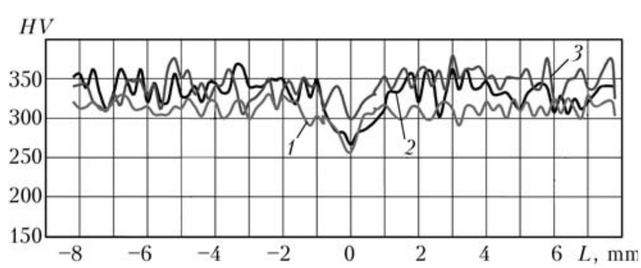

Figure 2. Hardness distribution in joints of rails of steel M76 (*1*) and E76F (*2*) made at the mode CF, and of steel E76F (*3*) made at the mode PF: L — distance from the fusion line

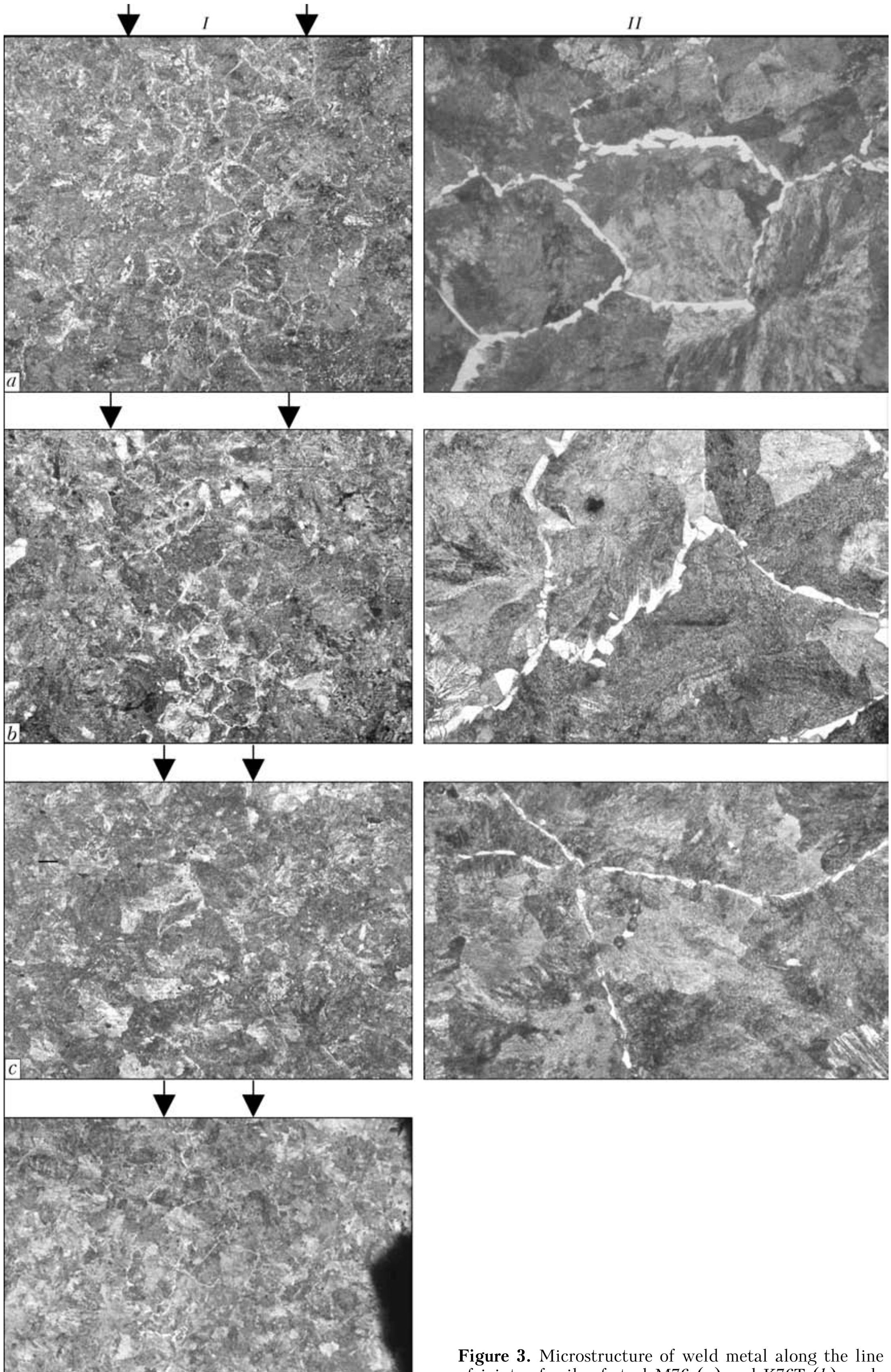

Figure 3. Microstructure of weld metal along the line of joints of rails of steel M76 (*a*) and K76T (*b*) made at the CF mode, and also of steel K76T (*c*) and U76V (*d*) made at the mode PF: *I* — ×100; *II* — ×500

those specimen, where the highest amount of defects like oxide films and DS were revealed in the fractures, especially when they were located at the edge of rails flange, which is subjected to tension during bend tests. However this is not the only reason of $f_{\rm defl}$ and $P_{\rm bend}$ values decrease at the tests.

In some specimens the oxide films were not revealed in the fractures, however the mentioned characteristics had the lower values than required. It can be caused by the formation in the weld metal of a structure component with the reduced ductile properties. Ferrite is the obvious component which is precipitated along the boundaries of grains of primary austenite along the joint line, in the rest the microstructure of joints of rails being examined is differed negligibly (see Figure 3). It is noted in the work [2] that increase in content of free ferrite in the heat-hardened rail joints reduces their strength and resistance to the crack initiation.

In flash-butt welding the melt layer, formed on the flashing surface, exerts significant influence on the formation of metal structure along the joint line. The melt layer actively interacts with the gases, evolved in a spark gap, including with the air oxygen, resulting in decarbonization both of the melt, and also near-contact layers of metals being joined due to the high diffusivity of carbon, and also to the saturation of the melt with gases, in particular, with oxygen [5].

During upsetting the full removal of melt from the gap does not take place. The melt preserves on the structure boundaries in the near-contact layer of the metal being in the solid-liquid state, thus resulting in formation of decarbonized and gas-saturated layer along the joint line. It leads to the precipitation of free ferrite along the boundaries of primary austenite grains and noticeable reduction in ductility due to the increase in oxygen content making the structure boundaries brittle. The content of free ferrite is an indirect sign of degree of change in chemical composition of the metal along the joint line.

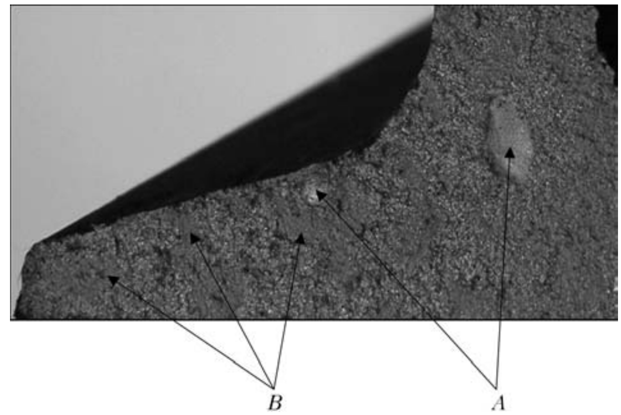

Figure 4. Fragment of fracture of welded joint of rails of steel E76F: defects of group *A* — oxide films; *B* — DS

In the rail joints of steel K67T, produced at the mode CF, the width of area with ferrite precipitates is larger than that in the rails of steel M76 (see Figure 3). As the welding conditions of rails of mentioned batches are identical, this is obviously preconditioned by the presence of titanium in the steel com-

Table 5. Chemical composition (wt.%) of non-metallic inclusions

Grade of steel	Fe	Mn	Si	S	V	Ti
Rail steel						
M76	39.8–80.9	0.86–10.30	0.51–1.30	0.3–5.3	N/D	N/D
K76T	33.5–58.5	0.01–0.50	0.9–6.1	2.4–30.1	0.006	0.1–1.2
E76F	68.9–95.8	0.7–1.6	0.56–5.90	0.08–0.50	0.06–0.12	–
Fracture surface of rail welded joints						
M76*	45.8–79.1	0.9–5.3	1.2–10.3	0.8–10.1	–	–
K76T**	20.9–35.9	0–0.1	3.8–55.9	3.6–24.2	0.003	0.03–1.80
E76F**	22.8–37.5	0.8–1.3	40.1–54.5	3.6–24.2	0.07–1.30	0–0.48

Table 5 (cont.)

Grade of steel	P	Al	Ca	Cu	O	Mg
Rail steel						
M76	0.02	N/D	0.03–5.30	0.01–0.11	6.3–55.2	
K76T	0.02	0.001–5.300	0.1–5.3	0.01–0.15	11.9–30.5	0.2–0.5
E76F	0.01	0.29–0.31	0.55–5.17	0.12–0.16	1.86–21.80	0.4–0.7
Fracture surface of rail welded joints						
M76	0.007	N/D	N/D	Single inclusions		
K76T	0–0.24	0–0.48	0.1–2.8	Particles on DS		
E76F	0–0.14	0.1–2.8	0.6–3.2	Particles on DS		

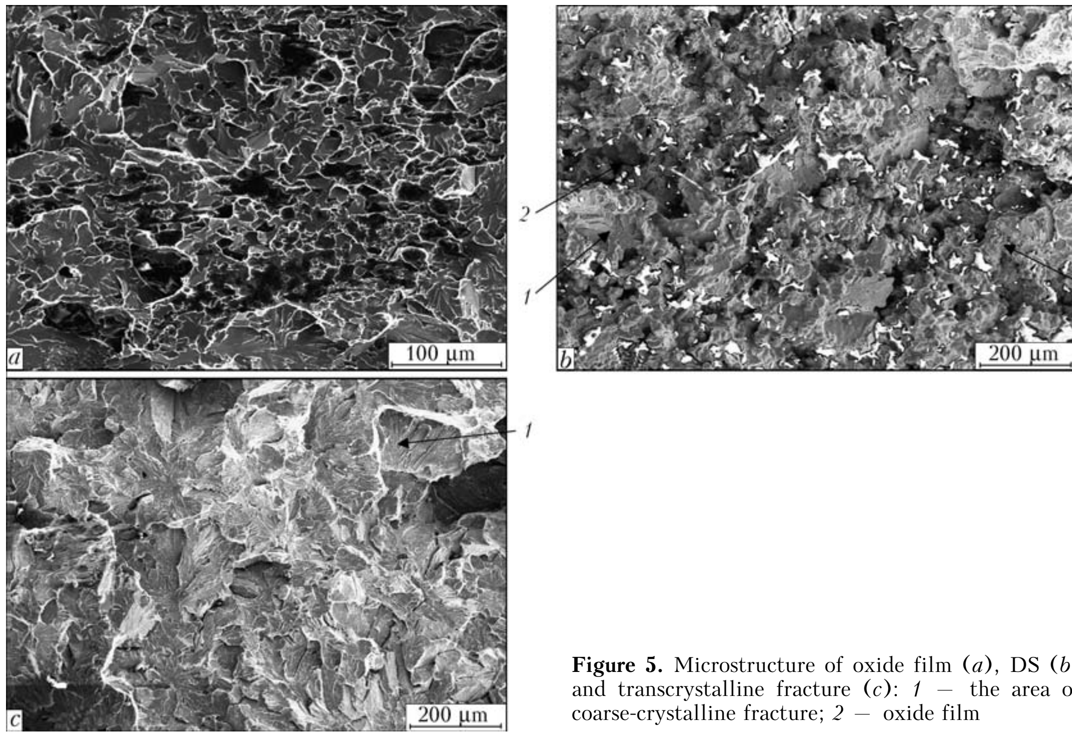

Figure 5. Microstructure of oxide film (*a*), DS (*b*) and transcrystalline fracture (*c*): *1* — the area of coarse-crystalline fracture; *2* — oxide film

position, which widens the area of α-phase existence in iron alloys [6].

The results of carried out investigations allow making a conclusion that the deterioration of weldability of high-strength rails of modern production in comparison with the standard ones of the 1990s production is due to one of dominating factors, namely the increased content of non-metallic inclusions in rail steels, especially those containing vanadium, titanium and aluminium. Therefore, it is necessary, first of all, to search for ways of decreasing the volume fraction of non-metallic inclusions and to establish appropriate regulating documents.

It is known from the practice of flash-butt welding [3] that to decrease the probability of formation of oxide inclusions and DS in the joints it is necessary to apply the soft welding conditions, characterized by a low gradient of temperature field. This enables the increase in duration of crystallization of molten metal on the flashing surface and facilitates the removal of refractory oxide structures in the process of deformation. These conditions are used in flash-butt welding of heat-resistant alloys, and also high-alloyed steels, containing the elements which form high-melting oxides of chromium, titanium, tungsten [7]. The mentioned conditions were also tested in welding of rail batches, where chromium and nickel were used as alloying elements. Here, the rails were not subjected to heat hardening. The application of soft conditions in welding of heat-hardened rail batches under investigation has led to the reduction of average characteristics of static bend tests due to increase in volume fraction of ferrite in the metal of welded joints. To suppress its formation, the severe conditions of heating with a high gradient of temperature field are required. To realize simultaneously the above-said problems on the base of traditional technologies appeared to be impossible.

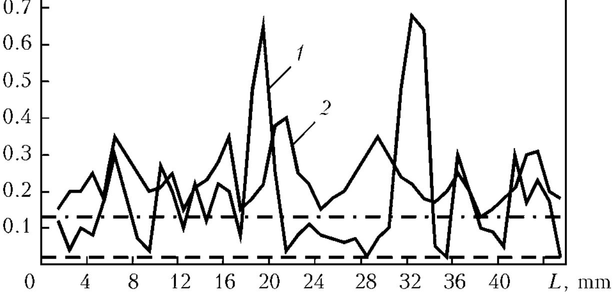

Figure 6. Thickness δ_m of liquid metal (melt) on the surface of flashing of rail head of steel E76F in welding using continuous (*1*) and pulse (*2*) flashing: – • – – maximum melt thickness at the mode PF; ----- — the same at the mode CF

It was established by investigations that formation of oxide structures takes place mainly at the places located on the flashing surface, where the melt has the minimum thickness (Figure 6), which is caused by an explosion-like destruction of contacts at the final stage of their existence [3]. During the explosion the liquid layer is torn away, and the melt is practically absent or reduced to hundredth of millimeters. The duration of this layer crystallization is minimum in the near-contact area even at a low gradient of temperature field, that leads to crystallization of the melt and formation of oxide films before the deformation of edges of the parts. The search for methods of producing the more uniform distribution of a melt and increase in minimum values of its thickness promotes the formation of quality joints at the sufficiently high gradients of temperature field in HAZ. It was estab-

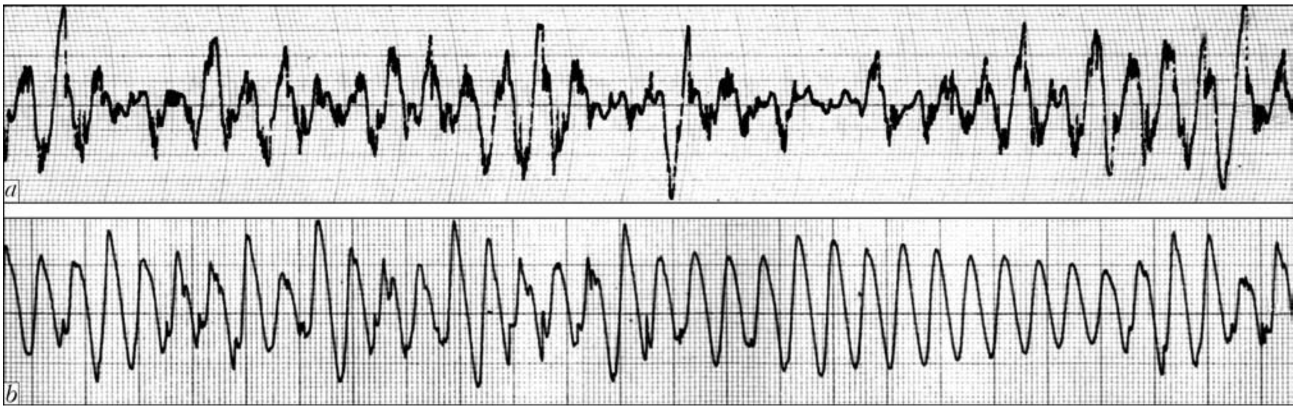

Figure 7. Oscillograms of current I = 1000 A in welding rails of steel M76 using continuous (*a*) and pulse (*b*) flashing

lished that explosions occur at the maximum voltage values. The decrease in their values allows the suppression of explosion-like process and providing the more uniform distribution of the melt.

However, at the strictly preset programs of voltage change its decrease can cause the interruption in the flashing process and transition into resistance heating. Due to the simultaneous control of instant values of voltage and feed speed, the radically new process has been developed, called a pulse flashing [8]. During the pulse flashing the duration of flashing periods, characterizing the explosion-like destruction of contacts (Figure 7, *b*), is much lower than that in the continuous flashing (Figure 7, *a*). During the pulse flashing a smooth flashing surface is provided by suppression of explosion-like destruction of contacts, and the minimum thickness of melt δ_{min} is 3–4 times increased as compared with a canonic flashing (curve *2*, Figure 6). Here, the higher efficiency factor of welding process is provided due to decrease in losses of power in destruction of contacts and increase in heat concentration. The near-contact layers of metal of 3–5 mm width are heated up to high temperature (Figure 8, curve *1*) at narrower HAZ than that in the continuous flashing (Figure 8, *a*, curve *2*). The heat duration is greatly reduced (2–3 times) in comparison to the basic condition, and the HAZ width is 1.5–2 times decreased (Figure 9). The larger part of deformation during upsetting comes to the near-contact layers, that provides the more complete removal of oxide structures. The high degree of deformation, minimum duration of heating in combination with high cooling rates promote the formation of more fine-grained structure in the metal of weld central part and the suppression of free ferrite formation along the grain boundaries (see Figure 3, *c, d*). The width of ferrite inclusions on the grains boundaries is smaller, they do not form a continuous lattice as in the specimens welded at the basic condition (see Figure 3, *a, b*). In spite of increase in the cooling rates caused by high gradients of the temperature field, the appearance of hazardous quenching structures is not observed in HAZ in welding with a pulse flashing of rail batches of steels E76F, K76T and U75V. The structure of a sorbite-like pearlite prevails which is transferred to the bainitic one at some areas. In the weld center of rails of steel E76F the hardness is close to the similar values of base metal (curve *3* in Figure 2). The test results of all batches of rails, welded by a pulse flashing at a preset condition, correspond to standard values indicated in Table 4. The non-metallic inclusions were not revealed in rail fractures.

It was established during the process of investigations, that to obtain stable characteristics of high-strength rails is possible at the absence of deviations of main parameters from the preset values including those influencing the power input in welding. The admissible range of heat temperature change should not exceed 50° (hatched area in Figure 8).

The realization of technology of welding with a pulse flashing under industrial conditions became possible after the development of new systems of automatic control of pulse flashing, as well as searching for the new algorithms of this process control at the E.O. Paton Electric Welding Institute. Instead of strict programming of main parameters, accepted in the continuous flashing or with the resistance preheating, the self-setting system of parameters control has been developed which allows the maintaining of optimum condition of stable flashing and heating under

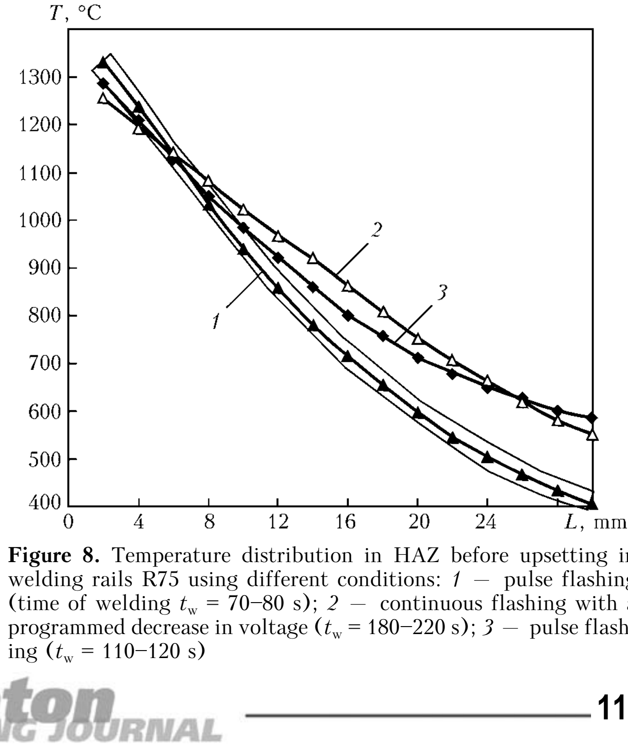

Figure 8. Temperature distribution in HAZ before upsetting in welding rails R75 using different conditions: *1* — pulse flashing (time of welding t_w = 70–80 s); *2* — continuous flashing with a programmed decrease in voltage (t_w = 180–220 s); *3* — pulse flashing (t_w = 110–120 s)

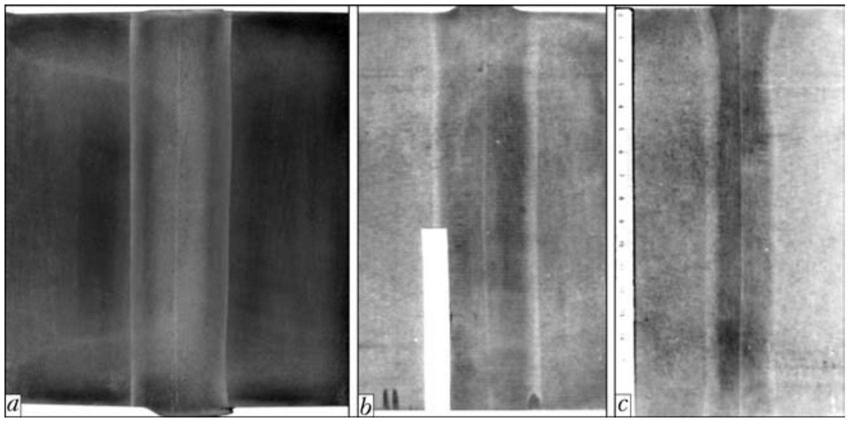

Figure 9. Macrostructure of welded joints of rails: *a* — steel M76 (mode CF); *b, c* — steel E76F, modes CF and PF, respectively

the real industrial conditions independently of changes in service conditions (fluctuation in mains voltage and environment temperature).

The industrial realization of flash-butt welding technology with a pulse flashing required the significant modernization of the rail welding equipment.

Over the recent seven years the new generations of stationary (Figure 10, *a*) and mobile (Figure 10, *b, c*) rail welding machines have been developed at the E.O. Paton Electric Welding Institute, which allow welding of heat-hardened rails of different purposes using the pulse flashing process. The technical characteristics of machines K1000, K920 and K922

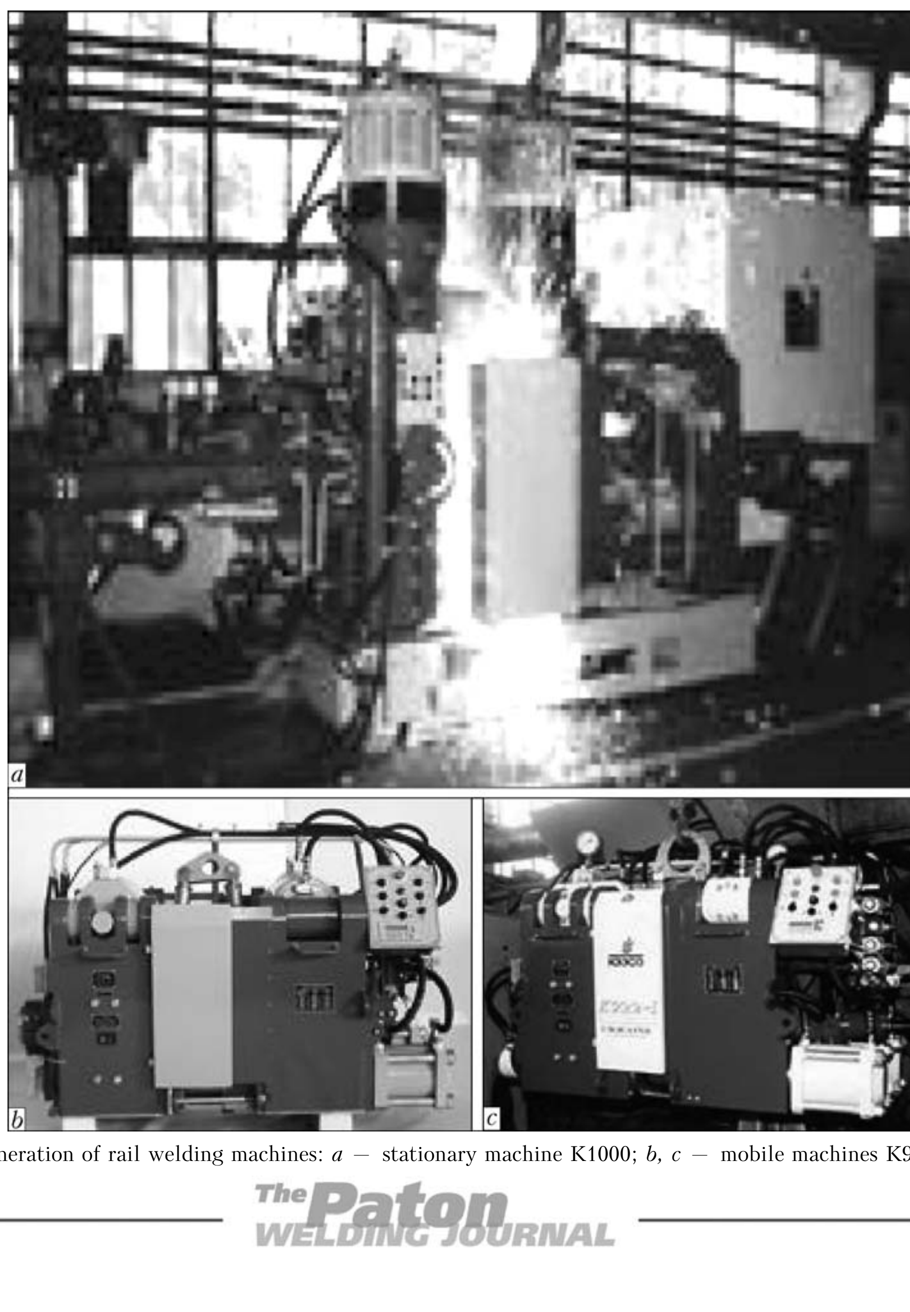

Figure 10. New generation of rail welding machines: *a* — stationary machine K1000; *b, c* — mobile machines K920 and K922

Figure 11. Mobile rail welding complexes: *a* — «Holland»; *b* — «Plasser»; c — «Norfolk»; *d* — KSM 005

are given below. The new equipment has the noticeable difference from the well-known rail welding machines:

Technical parameters	Types of machines		
	K920	K922	K1000
Rated voltage of mains, V	380	380	380
Rated current (50 % duty cycle), A	540	540	800
Rated power (50 % duty cycle), kV·A	210	210	300
Operating pressure in hydraulic system, MPa	125	210	160
Force, kN:			
upsetting	1000	1200	900
clamping	2500	2900	2000
Mass, kg	3000	3500	8800
Time of welding of R65 rails	180/90*	180/90*	180/70*

*Numerator — continuous flashing; denominator — pulse flashing.

The machines are equipped with a quick-response hydraulic drive and voltage controller, allowing changing the speed of movement of large-tonnage rail sections synchronously with changes in instant values of current and voltage.

The welding circuit of machines has a low (less than 100 μOhm) resistance due to the application of welding transformers, built-in into casings, and elements of the secondary circuit, thus providing the steady process of flashing at low voltages.

The new generation of machines is characterized by the higher forces of clamping and upsetting that allows welding of long rail sections with a simultaneous their tension, using increased specific pressures required for welding under rigid conditions.

The computerized system of welding parameters control allows automatic adaptation of welding conditions to the real changes in service conditions (fluctuation of mains voltage, welding circuit resistance, environment temperature). The system realizes also evaluation of joints quality just after the welding, the evaluation results are put into the memory of electron carriers.

The new rail welding machines are characterized by the high power efficiency in contrast to the foreign models using flash-butt welding technology with the preliminary resistance heating. The machines of the E.O. Paton Electric Welding Institute design have 2–3 times lower capacity and consumption of power.

Since 2002 the new generations of mentioned rail welding machines designed at the E.O. Paton Electric Welding Institute are serially produced by KPEWE, with which the Institute is collaborated on the license base. This equipment is under the successful service in the CIS countries and delivered for export. In Ukraine and Russian Federation about 60 stationary machines of K1000 type, as well as field machines (32 machines of K900 type, 41 machines of K920 type, 50 machines of K922 type) are operating now. About hundred of rail welding machines of K920, K922, K1000 types is operating in many foreign countries (USA, Canada, Austria, China, Australia and others). The marketing, delivery and service of these machines are realized by Canadian «Paton Holding Inc.» company and American «Holland» company in accordance with available cooperative agreements. In realization of all these works many new interesting technologies on organizing the construction and reconstruction of high-speed railways have appeared at the E.O. Paton Electric Welding Institute. For this purpose a lot of different mobile rail welding complexes, created on the basis of mentioned welding machines, are used (Figure 11).

CONCLUSIONS

1. The weldability of heat-hardened rails of modern production depends greatly on the composition of non-metallic inclusions in the rail steel which are not related to the regulated components.

2. The presence of impurities on the basis of oxides of vanadium, titanium and aluminium in steel deteriorates the weldability as it contributes to the formation of oxide films in the joints and increase in free ferrite content along the grain boundaries of primary austenite.

3. In welding of heat-hardened rails of steels K76T, E76F, U75V at the flash-butt welding conditions with a continuous flashing, approved by the standards of Ministry of Rail Roads of Ukraine and Russian Federation for the standard rails, it is impossible to provide the stable quality of joints.

4. The developed technology of welding with a pulse flashing of heat-hardened rails, contained the impurities of the mentioned composition, allows attaining the required quality of joints.

5. The application of the new rail welding technology based on the application of the flash-butt welding with a pulse flashing requires updating of design of rail-welding machines and control systems.

6. The new generation of stationary and mobile rail welding machines have been developed, providing the realization of technologies of welding with a pulse flashing. The serial production of the mentioned equipment has been mastered at KPEWE.

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MODERN TENDENCIES IN THE ERECTION-WELDING WORKS

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The paper describes the modern welding technologies used in site works in construction of main pipelines, pumping and compressor stations, technological pipelines in power engineering and chemistry, large-sized structures.

Keywords: *arc welding, site works, MAW, MIG/MAG-processes, STT-process, pipelines, stations, large-sized structures*

In annual volume of welding manufacturing the erection-welding works occupy an important place. In spite of efforts to reduce their volume at the construction-erection object proper by using ready large assembly blocks and modules, stored according to isometric scheme of tubular units and transport of oversized equipment, their share in the total volume still remains considerably high. Also there are special peculiarities during the performance of these works which make them more complicated and labor-consuming: the great influence of climatic and atmospheric conditions; different spatial positions of welded joints, making the application of mechanized methods and technologies difficult; complications in providing monitoring and quality control over the welding process; absent of more skilled personnel as compared with that available in the shop conditions.

Reinforcement of reinforced concrete structures. This is mainly the profiled reinforcement of class A-III. Using welding the reinforced frames of reinforced concrete structures are manufactured, subjected to concrete monolithing, or welding of ready reinforced-concrete elements into the so-called as-assembled reinforced concrete structures is performed. All reinforced nets and embedded fittings are supplied from special shops. At the erection the manual electric arc welding (MAW) is used as well as thermit and bath methods of welding. Due to simplicity of MAW at the performance of site welding in the confined areas, especially for smaller sizes of reinforcement, it remains the main welding method, irrespective of using the semi-automatic welding methods with a flux-cored wire (the so-called bath welding).

Main pipelines, pumping and compressor stations. At the present moment there is a real boom in construction of these structures. For semi-automatic welding of site joints, the large gas-pipeline construction companies use the welding columns. In particular, the Bulgarian company «Gazstroymontazh» is using a column of «CRC» company over many years (Figure 1). The erection-welding works are performed under any conditions: in permafrost regions, deserts, in ships at laying out into underwater trenches, in rocky areas, in passing the agricultural lands and rivers. The main welding methods are MAW and MIG/MAG using solid and flux-cored wire. The weld root layer of the welded joint is made by MAW using cellulose-coated electrodes, hot pass and filling with basic-coated electrodes. This method is preferable for pipelines of up to 500 mm diameter. Moreover, the quality of a complete penetration of a root weld is guaranteed, and due to a hot pass hydrogen content in deposited metal is reduced to 10 ml/100 g of deposited metal. This method will remain basic in the next 10 years, especially for the pipes of small diameters.

The MIG/MAG welding method using solid and flux-cored wire is also very widespread, especially the semi-automatic downward welding of pipes using self-shielding flux-cored wire. The results of testing pipe steel welded joints on mechanical properties in accordance with AWS standard are given in Table 1, and on diffusive hydrogen content in the metal weld — in Table 2.

The Lincoln Electric company has developed a group of flux-cored wires of «Innershield» grade, which is recommended for welding of joints of main and industrial pipelines. The «Innershield» wire is designed, in particular, for welding of high-strength pipe steels, widely spread at present. It can provide the continuous quality of performed welds on most low-alloy steels up to class X-80 (K-65).

Figure 1. Welding column of CRC company for automatic welding of site joints

Table 1. AWS test results

Electrode	Number of passes	σ_t, MPa	σ_y, MPa	δ, %	KCV, J/cm^2, at temperature, °C		Hardness by scale R_b
					−29	−40	
NR-204H E71T-GS	1	539–560	N/R	N/R	N/R	N/R	–
NR-207/207H* E71T8-K6	Several	525–560	420–497	22–30	68–289	51–170	85–90
NR-208H E91T8-G	Several	630–651	567–574	25–27	68–187	42–170	90–95

*Specimens were subjected to ageing for 48 h at T = 105 °C.

Table 2. Typical test results on diffusive hydrogen content in weld metal in accordance with AWS A4.3–86 (mercury method)

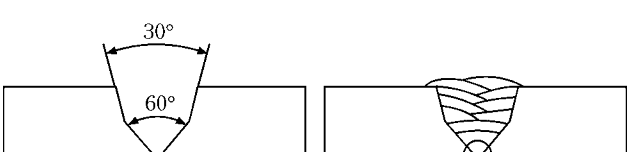
Diameter and wire grade	H_d, ml/100 g
0.068" (1.7 mm) and 5/64" (2.0 mm) NR-207	6–13
0.068" (1.7 mm) and 5/64" (2.0 mm) NR-207H	5–8
0.068" (1.7 mm) NR-208H	4–5
5/64" (2.0 mm) NR-208H	5–7

The wire application allows considerable simplification in overcoming the situation of a poor assembling of the joint, which is often occurred in operations at the route and also allows reducing the total time of welding. The self-shielding flux-cored wire is far more resistant to negative influence of wind and extreme temperatures.

The «Innershield» wire is in compliance with standard API Std. 1104, and also with some international standards. This means in principle the stability in quality, minimum rejections and higher productivity.

The «Innershield NR-204H» grade wire is recommended mostly for welding of weld root layer. The «Innershield» NR-207, NR-207H and NR-208H grades are designed for welding of hot, filler and finishing layers.

Working with «Innershield» wire it is possible to use a combined edge preparation of the joint. To simplify the welding process and to improve the mechanical properties of a joint (Figure 2) in making the filling and finishing layers, the technique of welds layout is recommended. To achieve crack resistance and optimization of hardness level, it is necessary to apply preheating and monitoring of transition temperature, which is especially important in multi-pass welding of pipes with a large wall thickness.



a *b*

Figure 2. Scheme of edge preparation (*a*) and layout of welds in multi-layer welding (*b*)

The work conditions, specific requirements of applied standards, stressed state of a joint, level of alloying and other conditions can lead to necessity of using preheating and monitoring of the transition temperature.

Over the recent years the implementation of STT welding technology is really challenging in semi-automatic and automatic welding of pipelines. Its application offers many advantages, in particular in construction and site works.

The principle of STT-process lies in transfer of metal being deposited into a weld pool owing to surface tension forces (Figure 3).

The STT-process of semi-automatic and automatic welding has been realized on the base of INVERTEC STT II current source, designed by Lincoln company, which offers several advantages: in welding of pipes the STT-process (process of metal transfer by surface tension forces) reduces the labor consumption in making the root weld of pipe joint along the open gap and provides the better formation of reverse bead and fusion of edges and also minimizes spattering and smoke. The STT-process provides the noticeable reduction in diffusive hydrogen content in the root pass of multi-layer welds (Figure 4). This process differs from conventional welding with a short arc in shielding gases by the fact that welding current is controlled

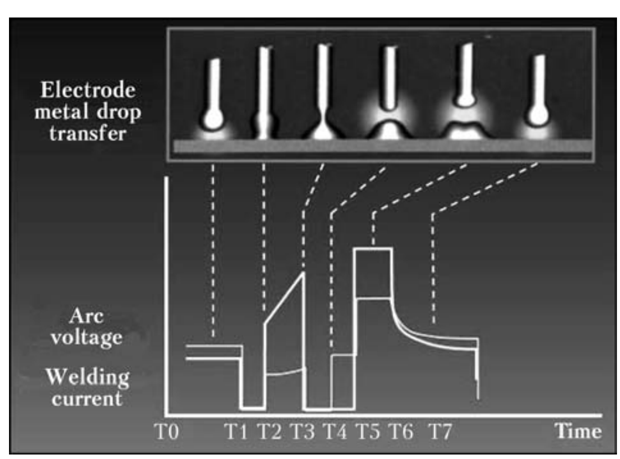


Figure 3. Scheme of STT-process

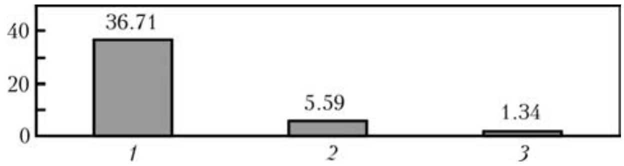


Figure 4. Dependence of diffusive hydrogen in weld metal on welding method: *1, 2* — electrodes with cellulose and basic coating, respectively; *3* — STT-process

here independently of the wire feed rate. Moreover, there are no splashes of molten weld pool in metal transfer, typical for the traditional methods of welding. This reduces the degree of weld pool stirring with a base metal, spattering and smokes, and provides also the more precise control of weld pool and penetration by the operator.

Thus, unlike MAW with rod electrodes, this process provides the higher reverse bead with a larger volume of deposited metal, that allows removing the aligning device just after making the root weld (Figure 5); low hydrogen content in weld metal; high productivity, high deposition rate and efficiency, and also duty cycle value.

The leading companies carry out lab tests on welding of main pipelines using laser technologies. In this case the edge preparation and welding process itself are performed exclusively quick and guarantee the high quality. The problems of reliability of equipment are also solved.

Nowadays a hybrid method of laser welding is applied. The ESAB company offers hi-tech systems of hybrid laser-arc welding (HLAW), which ensure the high efficiency in welding of beams, pipes, vessels and panels. In-process control is performed in a real time through the feedback. The application of hybrid laser welding guarantees the highest quality of welding thick materials for various types of welded joints. The quality of welded joints is increased, expenses are decreased due to reduction in deformations.

The HLAW combines the advantages of laser welding (deep penetration, reduction in heat input, narrow HAZ) with the advantages of conventional MIG/MAG welding (large variety of welded joints; filling of gaps of contaminated surfaces; control of welded joint metallurgy; low cooling rate preventing brittleness of welded joint).

Technological pipelines. Site welding in power engineering and chemistry. This is mainly welding of low-alloy and heat-resistant steels in heat-and-power engineering and stainless steels in chemical and food industry.

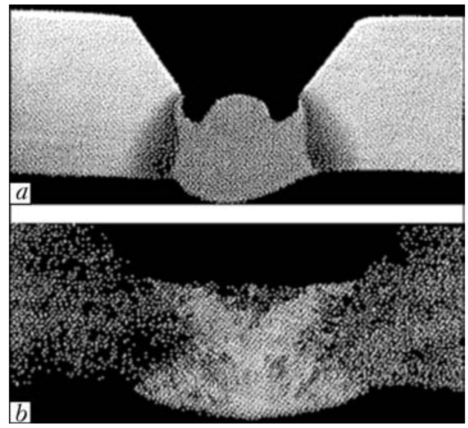


Figure 5. Macrosection of welded joint performed using MAW with rod electrodes (*a*) and automatic STT welding (*b*)

Figure 6. ESAB orbital machine A21 PRD

Nowadays the main method of their welding is argon arc TIG process or performance of root weld using argon arc process and filling pass using electrodes. Some companies have also developed orbital welding machines, which can be applied in site conditions. For instance ESAB offers orbital machine A21 PRD Orbital (Figure 6).

Depending on the wall thickness and diameter of pipe being welded the different methods of making joints have found application (Figure 7, Table 3).

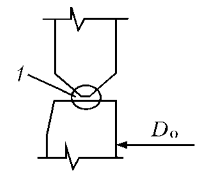
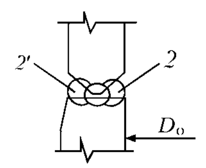
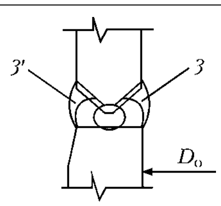
Large-sized structures and constructions. They include cylindrical and spherical tanks, column equipment for chemical industry, blast furnaces, silos and kilns for cement industry.

Table 3. Design of welded butt joints of pipes

Welding method	Design sizes				Outer diameter of pipe D_o, mm
	S, mm	*a*, mm	*b*, мм	α, deg	
MAA	< 5	–	–	$30^{\pm 3}$	> 100
C (MAA)	> 10	≤ 0.5	1.5	$10^{\pm 2}$	> 133
C (AAA)	> 10	≤ 0.5	1.5	$10^{\pm 2}$	> 133

Note. MAA — manual argon arc; C (MAA) — combined: root — manual argon arc; C (AAA) — combined: root — automatic argon arc.

Table 4. Welding conditions of horizontal welds of tank wall prepared for automatic site welding

Conditions of semi-automatic shielded-gas welding						
Weld layer	Scheme of layers layout	Wire diameter, mm	Current, A, polarity	Voltage, V	Root layer thickness, mm	Electrode stickout, mm
Root		1.2	150–190 DCRP	18–22	2–4	10–15
Conditions of automatic welding under the layer of ceramic flux						
Weld layer	Scheme of layers layout	Wire diameter, mm	Current, A	Voltage, V	Welding speed, cm/min	Electrode stickout, mm
Filling (simultaneous welding of both sides)		2.4 (2.5)	350–500	24–28	45–75	25–35
		3.0 (3.2)	430–520	24–32	50–70	30–35
Finishing (simultaneous welding from the both sides)		2.4 (2.5)	300–400	24–28	50–80	25–35
		3.0 (3.2)	350–450	24–30	60–80	30–35
Notes. 1. Submerged arc welding can be used with wire of 2.4 or 3.0 mm diameter. 2. Electrode inclination angle downwards from the normal to the plane within the ranges 0–30°. 3. Electrode inclination angle forward from the normal within the ranges 0–10°.						

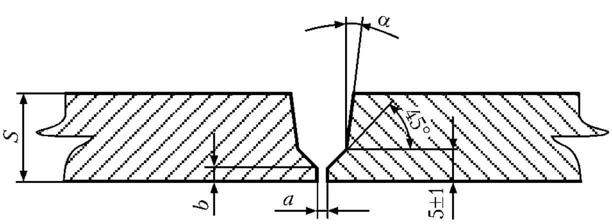


Figure 7. Scheme of pipe preparation for root weld using TIG method

For welding of small tanks and constructions of up to 10 mm wall thickness MAW or MIG/MAG welding with solid and flux-cored wire is used. However the automatic welding of horizontal welds is obligatory used for the large constructions, for example, for tanks (Figure 8).

Advantages of the new technology of automatic welding of horizontal welds (Table 4) are as follows: simplified fit-up of girths in site assembly; providing a complete penetration of root weld by a prewelding; achievement of higher productivity at the guaranteed quality.

It should be noted in conclusion that, depending on the type of construction, technological outfit available for erection-welding works, different welding methods are offered: MAW, semi-automatic or automatic.

In future the volume of MAW will be reduced owing to the wider application of MIG/MAG processes, and, in particular, to wide spreading the STT-process.

Figure 8. Casing walls of tank prepared for automatic site welding

NEW ASPECTS IN WELDABILITY RESEARCH — PREREQUISITES FOR TECHNOLOGY AND QUALITY ASSURANCE IN THE WELDING PROCESS

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The author report on a new concept of an integrated consideration of joinability, including all modern variations of modern joining processes is presented. Joinability takes into account all special influences on a joint component as affecting joint suitability in respect to material, joint capability for processing, and joint reliability for use and service. Special selected examples explain the self-contained concept of joinability, and solutions for the preparation of production are offered.

Keywords: *weldability, joinability, design, materials*

Product innovations with new solutions in joining-technology for an optimisation of the manufacturing process chain with new materials, which contribute to energy saving, to lightweight construction, and thus to the indulgence of the world-wide reserves of raw materials, are possible with the German potential of qualified specialists and their know-how and thus contribute directly to the keeping and development of the advantages of Germany's industrial production. In this way, ideas of research into areas of joining technology take direct influence on development, manufacturing and quality of products. Concurrently, they show connecting factors to the economically significant segment of restoration of the products manufactured with new materials and material compounds (Figure 1).

Definition of joinability. Joinability (Figure 2) takes into account all the special influences to a joint component affected by the joint suitability for material, the joint capability for processing and the joint reliability for use and service.

The complexity of the joining philosophy can be easily understood by the influences associated with the fusion welding process. The welding process e.g. characterises the heat-physical effects and the arc-physical effects, which are causing the weld pool and the deposited heat input into the components of materials with special material properties.

The weld pool interacts with the solidifying weld metal as well as the surrounding component about the temperature field, moving with welding speed. The welding pool acts together with shape, size and welding speed and special metallurgical effects on the liquid–solid transition of weld metal and HAZ. The temperature field moves with welding speed causing a field of heat-induced inhomogeneous thermal expansion and following shrinkage in the component. But the joined product has to guarantee, after this special joining process, all demanded properties of the material and designed product with respect to its later use.

The joint suitability deals with the realization of joining processing tailored to the guaranteed material properties of the joined material. It takes into account the technical utilisation of the whole joined component during service conditions and life-time.

In [2], Bollinghaus describes the current aspects of different discussion in Commission IX (IIW) especially under the point of view of weldability and behaviour (Figure 3).

The technical and economic development in modern joining technology is predominantly characterized by reduction of cost and weight. With respect to new structures and components, such challenges are met by advanced materials, innovative joining technologies as well as new design principles. With respect to existing structures and components, such challenges are met by respective life time elongation, often achieved by extensive repair procedures. In order to accomplish this, materials have to be selected exactly for the respective purpose. This means that base and filler materials will increasingly be chosen for a very

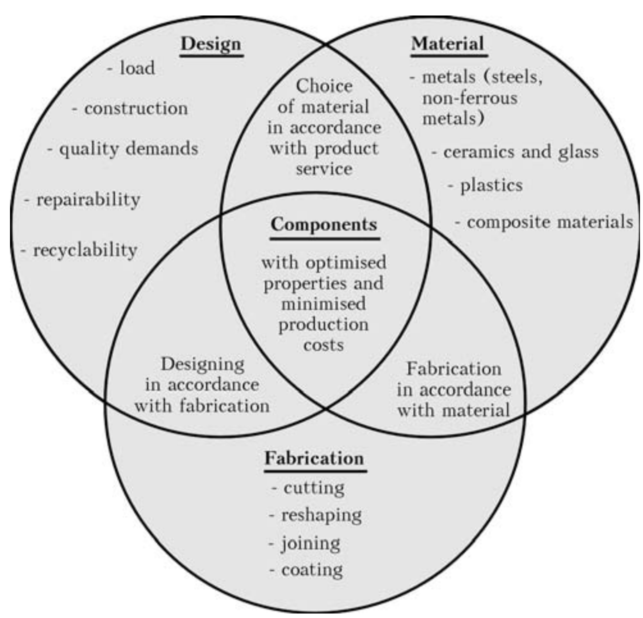

Figure 1. Joining technological correlation between structure, material and fabrication [1]

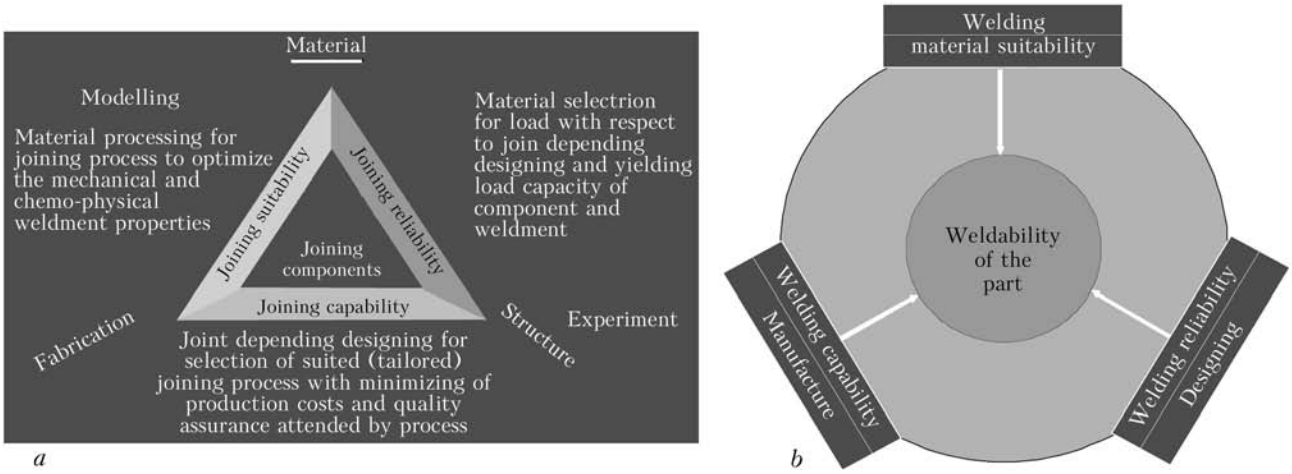

Figure 2. «Trinity» of joining suitability, joining reliability and joining capability (*a*), and weldability (*b*)

specific location of joined components to match the respective microstructural, mechanical and corrosion properties. Multi-material joints and life time elongating repair of welded structures and components will thus represent key technologies for the future. This does not only require new interface design technologies where the assessment of the optimum weldability (joinability) and the evaluation of the service performance have to be linked much more closely, if both not have to be assessed together. As can be seen by the simplified diagram below, evaluating the interaction of the selected materials with the respective design or way of construction will represent the main key towards a successful avoidance of failures of welded components during fabrication and service [2].

The joint capability summarises the technically efficient choice and adjustment of joining processing with respect to material and service properties of the product. It depends on designing for the joined component with respect to the special material (characterised by mechanical, chemical, thermal and physical material properties). The joint capability of a planned product exists, when there is a capable manufacturing process to join the components of an alloy, chosen and designed for the structure, to fulfil all designed service properties of the joined structure during its life-time.

The joint reliability proves the realisation of the designed joined component, taking into account the designing for service and processing with respect to the suited material.

Yushchenko et al. [3] discussed other interesting ideas for a new future concept of weldability. He integrates, among other things, analysis of available approaches to evaluation of «weldability» and standards in force in different countries and organisations, such as ISO 581–1980, DIN 8528 (Germany), TWI (Great Britain), Bratislava Institute of Welding (Slovakia), GOST 2601–84 (USSR), DSTU 3761.1–98 (Ukraine), and AWS. The analysis (of the Paton Institute) shows that:

- in the absolute majority of cases, «weldability» is evaluated qualitatively and subjectively, on the «yes» or «no» principle (i.e. the material is weldable or unweldable);
- the term «weldability» of materials is treated as a philosophical concept, namely «the ability», «takes place», «considered to be susceptible to welding to an established extent» etc., thus implying a subjective evaluation method;
- it is stated in some cases that «weldability is the property (meaning the ability) of metal to form a welded joint». This definition indicates neither what this property is nor how it can be measured. Therefore, this approach is also a subjective evaluation;
- almost all of the above definitions of «weldability» note that it is necessary to use «a corresponding

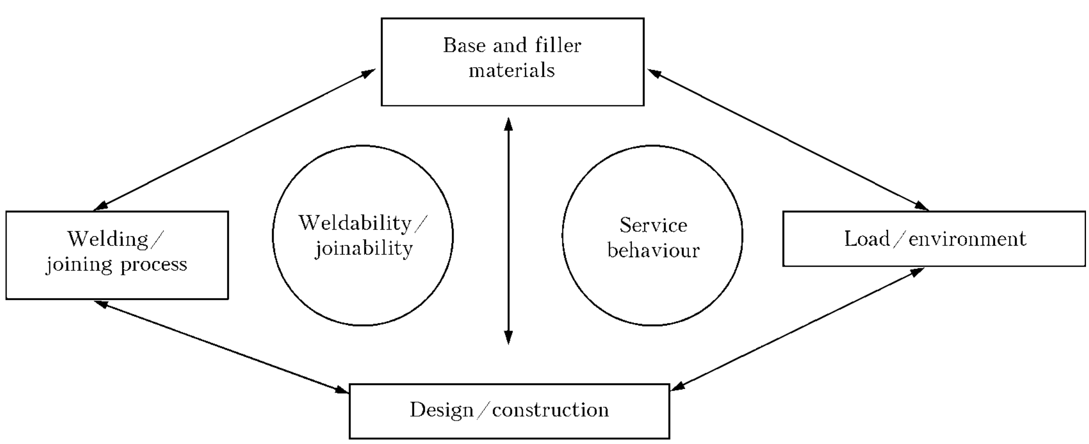

Figure 3. Interaction of the selected materials with the respective design and fabrication and service [2]

Weight reduction by light-weight materials [5]

Material		Mass reduction, %	Relative cost (per part)
предлагаемый	Replaced		
High strength steel	Mild steel	10	1.0
Aluminium	Steel, cast iron	40–60	1.3–2.0
Magnesium	Steel, cast iron	60–75	1.5–2.5
Magnesium	Aluminium	25–35	1.0–1.5
Glass PMC	Steel	25–35	1.0–1.5

technological process», or «a certain process and a certain technology», or «susceptible to welding by any method and using no special measures» (the latter refers to the case of perfect weldability), or «an established technology», or «a corresponding welding procedure». That is, the influence of a technology as it is on weldability is just mentioned. Moreover, recommendations to allow for the influence of a technology on weldability are of a conditional character [3].

Innovative materials and their joinability. Technical product-developments necessitate the use of new and innovative materials, such as: light-weight and high-strength materials; high corrosion-resistant materials; high temperature materials; technical ceramics and glasses; composite materials; super-hard materials; materials for nano-techniques; optical fibre; electrical, magnetic materials; sensor-materials; gradient-materials; implant-materials, and biomimetic and multifunctional materials.

Figure 4 gives information about the rate of innovative materials used in production.

Magnesium and its alloys are used as construction materials mainly for weight reduction (Table). Typical areas of application are branches of defence and automotive industry, mechanical engineering as well as electronics and consumer goods industry (Figure 5).

In the last years important characteristic improvements have been obtained by innovative material developments, especially high purity alloys. Better corrosion resistance combined with acceptable strength properties are resulting from that.

However, an important prerequisite for the use as structural materials are suitable joining technologies and particularly welding methods for different applications. In most industries (automotive, defence and other industries), joining by fusion welding is the first choice, because of its high productivity and the low costs of the created joints.

In fusion welding, the material can be molten by different heat sources. When a laser is used, the energy of the beam is concentrated to a small area so that a very accurate weld edge preparation is necessary. For most applications in automotive production, however, light metals are joined with arc welding methods as MIG and TIG welding. Frequently, welding of magnesium alloys is treated as equivalent to aluminium welding and the knowledge about welding of aluminium alloys is indeed advantageous for welding magnesium alloys. But for good results the arc welding process has to be adapted to the specific material properties.

Various studies of market economy show today that titanium secures a wide market in materials ranking directly after steel and aluminium [6–9]. Origin for this evaluation is the relatively good weldability for a plate thickness between 1 and 60 mm. The preferred application of titanium and its alloys in aerospace industry and special ship building, chemical industries as well as engineering for traffic, energy and medicine is due to its special material properties [8, 10]. There are three advantages for the application of titanium alloys: weight reduction by substitution of steel and nickel-base material; high heat resistance by

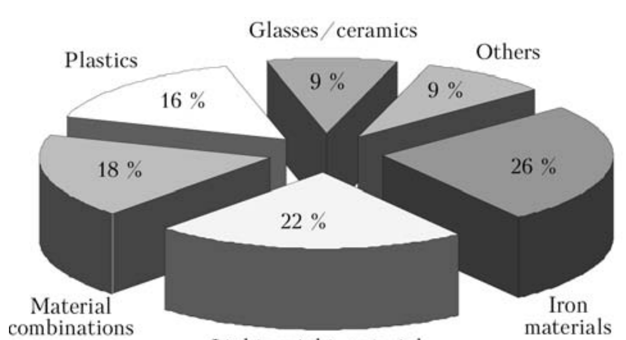

Figure 4. Business-questioning to materials used in production [4]

Figure 5. Standard applications of magnesium alloys in the different industries

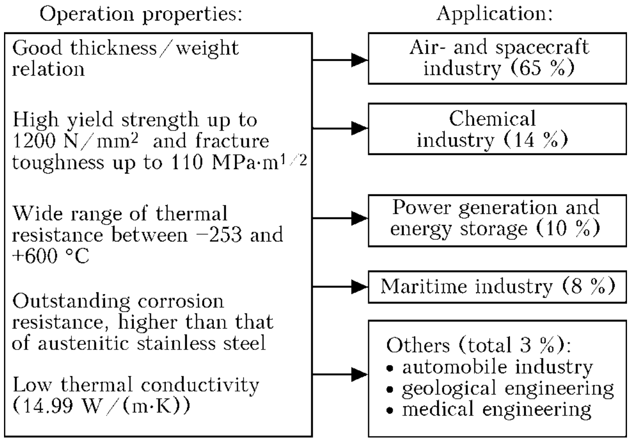

Figure 6. Operation properties and application of titanium and titanium alloys

substitution of aluminium, steel and nickel super-alloys; high corrosion resistance by substitution of aluminium and low alloyed steel.

Economical appropriateness of titanium appears in military techniques and civil applications (Figure 6). This refers to special equipment in aeroplanes and offshore techniques.

Pure titanium is successfully welded by electroslag, submerged arc (SAW) [11] and diffusion welding [12]. The application of metal inert gas-shielded arc welding (MIG) to Ti-alloys created the development of special equipment for gas shield, e.g. the protection gas chamber and the trailing inert gas shield, adapted to the gun. But the moving gas shield of both types of equipment can certainly not prevent the admittance of atmospheric gas to the weld pool. The more efficient welding with higher welding current and voltage decreases the gas shield. This technological deterioration of TIG results in the limited application of the high-frequent pulsed MIG welding of Ti-alloys [13] and the innovative creation of new process variations of the TIG welding with different degrees of welding process mechanisation [14].

The first variation is TIG welding, which is carried out also with additional gas shield and minimised heat input for reduced grain growth in Ti-alloys of the β-phase-type [15]. It is followed by TIG welding with tubular cored wire, based on flux admixture of alkaline metal fluoride to realise butt weldings about 4 to 16 mm plate thickness [13, 16]. The active powder TIG welding procedure is a specialised A-TIG welding procedure using active flux paste, overlaid on the metal surface before welding [13, 17–19]. The narrow-gap TIG welding applies a magnetically impelled arc between the non-consumable tungsten electrode and the Ti-plate of between 20 and 110 mm thickness [13].

Most advantageous application of beam welding techniques to Ti-alloys are electron beam welding for plates of up to 380 mm thickness and laser welding with additional gas shield (10–12 mm thick walls), whereas plasma welding may be neglected [15].

Resistance welding is preferred in the air craft-industries with up to 3.5 mm thick walls because of its thermal conductivity, resulting in short welding times without gas shield. But its application is connected with high requirements to weld preparation, e.g. plate edges cleanliness, pickling for removing oxide skins [10].

Large effort is being made for further tailoring the efficient clean technology because of high oxidation resistance during processing (resistance, TIG, electron beam and laser welding) for extended applications in military and civil industries [20].

Using an optimised welding procedure, friction welding guarantees high static and dynamic strength of the joints without any pores, grain growth in the heat affected zone and casting microstructure of weld metal. The short welding time prevents dangerous gas absorption and embrittlement [21], but bulging necessitates machining after welding.

Chemical process industry is the main customer for highly corrosion-resistant stainless steels and nickel-base alloys. Great demands are made on metallic materials for these applications, due not only to increasingly complex processes and corrosive environments but also to the chemical industry's need to extend equipment life, reduce the danger of accidents caused by corrosion damage, and ensure the highest possible product purity. Answering changes in the requirement profile, a large variety of materials for wet corrosion applications has been developed over the last 20 years. To these belong, amongst others, super-austenitic special steels and super-duplex stainless steels, offering high resistance to a wide range of aggressive media, including highly concentrated and contaminated nitric, sulphuric, phosphoric, hydrochloric and organic acids.

When, for instance, producing sulphuric acid one has to distinguish clearly between the different ranges of concentration and content of impurities of the acid and, accordingly, to choose the appropriate material for the equipment For the application with highly concentrated sulphuric acid (above 98 %), some alloys like X1CrNiMoCuN33-32-1 (alloy 33, Mat.-No. 1.4591) or X1CrNiSi24-9-7 (alloy 700 Si, Mat.-No. 1.4390) have been developed in Germany in the last few years. While alloy 33 is properly weldable using plasma, laser-beam or TIG welding with same-type filler metal [22], there are considerable problems with TIG welding of alloy 700 Si with same-type filler metal. These problems are, above all, the precipitation of brittle silicide phases (primary phases) in the weld metal and the high-heated areas of the HAZ and the precipitation of intermetallic phases (secondary phases) in the HAZ (Figure 7). The primary silicide phases cause a hard and brittle structure in the weld metal and a tendency to hot-cracking with a plate thickness above 6 mm. The secondary phases in the HAZ decrease corrosion resistance. Prerequisites to achieve good strength and ductility properties as well as keeping heat affected zones free from secondary phases are the application of laser-beam welding or a post-weld heat-treatment of TIG-welded structures [23]. It was also for these reasons that alloy 700 Si did not get accepted in practice despite its outstanding corrosion resistance.

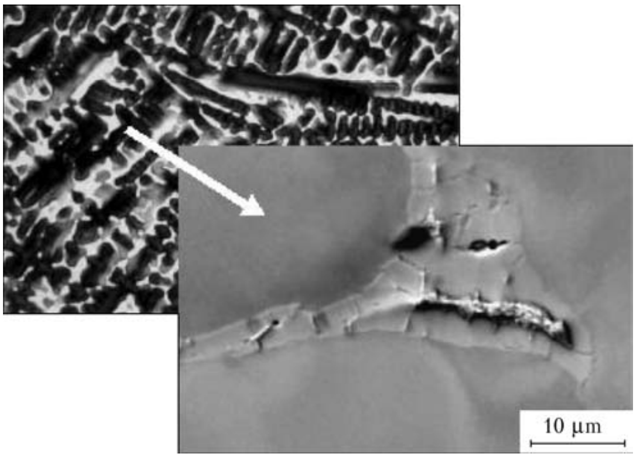

Figure 7. Silicide phases in the same-type TIG welded metal of alloy 700 Si [21]

Already now and even more in the future, the new materials of the energy technology require intensive research also in joining technology for the supply of appropriate welding methods and technologies. This seems to be one of the preconditions for implementing the political and ecological target of replacing nuclear energy production by conventional power plants that should be compatible with the environment and be technically feasible, and that should work at economically justifiable expenditure in the near future.

With the introduction of flue gas purification by desulphurisation and denitrification, the emission of acid-forming constituents was reduced to acceptable values. For the reduction of carbon-dioxide emission of coal power plants there is, however, only one solution: the increase of thermal efficiency. An improvement of efficiency can be attained only by higher steam parameters, i.e. particularly with increasing temperature and with increasing pressure. But in the future new, more efficient materials than being tested at present must be used. Already now, and even more so in the future, these new materials require intensive research work:

• a clear rise of the limiting parameters temperature and pressure took place with the advancement of the ferritic-martensitic steels, such as P91 or P92, and their application as super heater pipes, collector and steam pipes as well as their application in turbines. This efficiency is shown in intensified measure by high performance materials adapted for special applications, e.g. austenitic special high-grade steels and nickel-base alloys;

• nickel-base materials must be used more and more in the future. They offer a sufficient potential regarding strength and corrosion behaviour even at temperatures above 700 °C, however make much higher demands to the welding processing than the conventional corrosion-resistant steels;

Investigations regarding the application of orbital narrow gap TIG welding of pipes of X10CrMoVNb9-1 (ASTM grade P91, Mat.-No. 1.4903) with both cold and hot wire feeding were realised in our institute [24] (Figure 8).

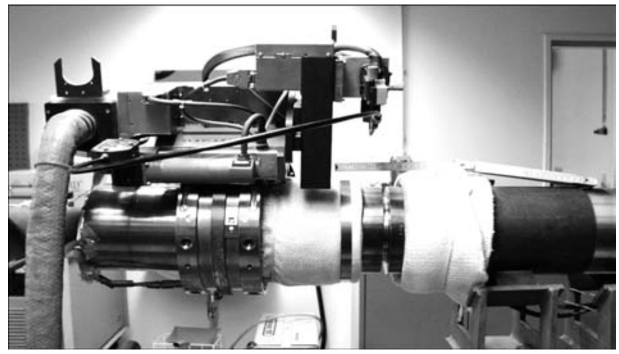

Figure 8. Welding equipment for orbital narrow gap welding [24]

ISO stress tests at temperatures between 610 and 630 °C have shown that hot wire feeding show better results than cold wire feeding, and orbital TIG welding has better values for creep resistance than manual TIG/MIG welding (Figure 9).

Structure components of fibre-reinforced composite materials, in particular of synthetic fibre-reinforced composite materials (SFC), have been found for years in industrial application with matured constructional design and technological variants. Technical problems and difficulties are often caused by non-optimal joining-technological solutions and the preparation of blanks for connecting SFC with each other and in combination with metal parts, which is still not convenient for industrial production. This is also confirmed by problem discussions of manufacturers and the common search of users and research centres for solutions for joining technologies suitable for series production including necessary filler materials, devices and equipment.

Joining-technological design and execution variants for metal fibre-reinforced composite materials, composite materials with metallic matrix (MMC), and oxide-dispersion-strengthened composite materials (ODS) are still unexplored areas at present. However, these new high-performance materials are already tested in pilot vehicles of automotive manufacture and on the ICE2-carriage. Specific adjustable material properties, e.g. better wear-resisting quality at disc brakes with lower weight, at the same time, make their application interesting also for other components for the construction of vehicles. International

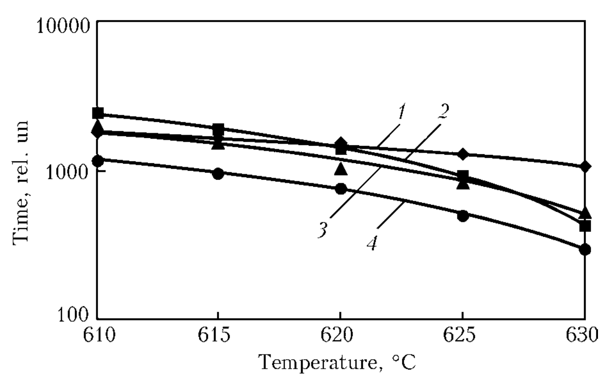

Figure 9. Results of ISO stress test of P91 joints [24]: *1, 2* — orbital TIG hot-wire welding with maximal and minimal interpass temperature; *3* — orbital TIG cold-wire welding; *4* — manual TIG/MIG welding

technical literature shows that MMC composite materials are not to be considered exotic materials any longer. In the case of its processing as a tool for cutting, boring and joining, the laser is gaining ever more importance. Therefore their industrial application requires concepts reaching from development and construction of new products over joining technologies suitable for series production up to process-integrated testing and quality control. Their application in mass production also presupposes, however, realisable repair and recycling concepts.

Technical ceramics and glasses offer characteristics which make them superior to other materials in certain cases of application (temperature, wear and corrosion resistance, low density etc.). That makes them interesting for industrial application in highly stressed components in vehicle, aeroplane and mechanical engineering as well as in space technology, electrical engineering, micro technology and tool making.

At present, insufficient reproducibility and lack of knowledge about technological possibilities of joining and mechanical characteristics of the joints prevent a wider industrial application of technical ceramics and ceramic metal composites. Welded and soldered joints, e.g. by diffusion bonding and ultrasonic welding, are possible and applied with joining technical ceramics with metallic intermediate layers (foils), though their physical binding mechanism, which would permit an optimisation and a verification of joining possibilities is still unknown. Additionally, there are large deviations in deformation and strength behaviour with combinations of ceramics and metals, which lead, on the other hand, to additional internal stresses in the compound. All this makes joining technology an inevitable technological process within the entire manufacturing process chain. However, extensive research must be done into manufacturing methods for large-scale production.

CONCLUSION

Innovative materials with their very special properties and functions will always demand new and more complex concepts for the assessment of a modern weldability as necessary prerequisite for technologies and quality assurance in the welding process of the future.

They have a pole position for the technical and economical acceptance of these innovations. Wide ranges of application in aerospace and chemical industries as well as in environmental, medical, electrical and power engineering could not be realised without using new materials. Joining techniques and processes are integrative part of a system of interconnected manufacturing processes and their quality management. For this reason, they must be taken into consideration from the very beginning of product development, design and dimensioning as well as manufacturing of components of new materials and material compounds. The use of innovative materials has brought about considerably higher demands to joining processing, than was the case with the previous standard materials.

With nominating numerous aspects for research in joining technology, the importance of solving joining-technical problems for series production techniques was emphasized. This is especially true for the use of new materials, in particular for the production and processing of fibre-reinforced composite materials, for the application of technical ceramics and glasses, and with innovative lightweight constructions. Joining processes and techniques are an integrated part of the system of interconnected manufacturing processes. Therefore they have to be considered in product development, in design and dimensioning and in manufacturing and quality assurance for a production of tomorrow, going along with new materials and material compounds for innovative products.

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APPLICATION OF FRACTURE MECHANICS METHODS FOR ASSESSMENT OF STRENGTH OF WELDED STRUCTURES

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The development of the methods of welds strength and durability assessment are the most actual trends in the science about materials strength. It is known that the state of material in the zone of joint weld differs from the state of the material that is joined by certain welding technologies. There are always different damages in the zone of the joint weld — defects, residual stresses that should be taken into consideration while calculating strength and durability of welded structures. The synthesis of some investigations on the influence of mentioned factors on strength and durability of welds using the concepts of up-to-date fracture mechanics of cracked solids (fracture mechanics) are given below.

Kewwords: *welds, strength, durability, crack, crack growth resistance, material fracture, operation life*

In order to characterise the general essence of the problem and the approaches of the theory of materials strength and fracture at the up-to-date level of the science about their physico-chemical properties let us consider the basic (classical and nonclassical) postulates of the fracture mechanics of materials for the assessment of their strength [1].

In the frames of the classic concepts about materials as some solids-continuums it is considered that the element in the solid under the internal forces action is in one of such states: continuous (C) or fractured (F) state. Transition of the material form C- to F-state is the fracture process (Figure 1, *a*) and it occurs instantaneously if the stress-strain state characteristics calculated by the assumed rheological model for a solid (for example, elastic continuum) attain some critical level. For example, if maximum tensile stresses reach the ultimate strength level σ_t of the material the material damages — divides into two parts (C→F transition, see Figure 1, *a*) and this happens instantaneously! If the maximum stresses σ_{max} are less than σ_t, the fracture will not occur and the structural element will retain its integrity (strength).

It is the classical postulate of the fracture mechanics. The assessment of materials and structural elements strength (including welds) using of this postulate is decreased to the construction (using the theoretical and experimental data) of some functionals

$$F_s(I_1, I_2, I_3, C_1, C_2, C_3 \ldots) \le 0, \qquad (1)$$

where I_1–I_3 are the invariants of stress tensor (or deformation), and C_1–C_3... are the constants that are obtained from experiments.

It is necessary to note that in the frames of classical approach it is impossible to provide the technical diagnostics of fracture or nonfracture of structural materials under the extreme conditions, for example to assess the strength of material with sharp stress concentrators — cracks. Besides the analysis of the experimental data of fracture processes shows that materials fracture is not the instantaneous through the whole body cross-section, it occurs gradually (in time) by crack propagation and this is not taken into consideration by classical approaches.

The main idea (concept) of nonclassical approaches that is the approaches of the modern fracture mechanics and materials strength can be formulated as (Figure 1, *b*): the transition of deformed materials from C-state to F-state is accompanied by a certain intermediate (In) state of the material. This state should be taken into consideration when solving the problem on material strength, particularly when the material of structural element contains crack-like defects (sharp stress concentrators). The In-states of the material are especially characteristic near the sharp stress concentrators (Figure 1, *c*). So, the local fracture of the material occurs according to C→In→F transition. This is the basic concept of the modern fracture mechanics and strength of materials including welds.

An important feature of the deformed solid regions, where F-states (regions of process) appear, is the fact that the material here is always deformed beyond the stress limit and the size of these regions is small (these are mezovolumes). Just in these regions of the material the intensive local plastic deformation, interaction with the environment, diffusion processes etc. occur.

Physicomechanical properties of the material mezovolumes (process zones) differ from the same properties of the basic metal. The minimum amount of the

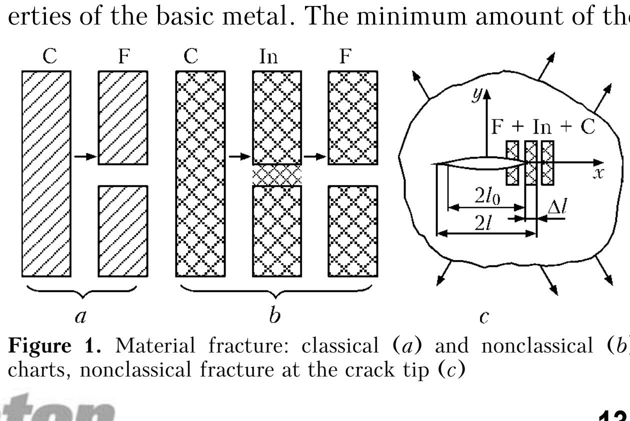

Figure 1. Material fracture: classical (*a*) and nonclassical (*b*) charts, nonclassical fracture at the crack tip (*c*)

energy that must be accumulated for the realisation of the formation of new surface units was supposed [2] to be the basic physico-mechanical characteristic of this volume. This characteristic is considered as the ability of the material to resist fracture (the crack propagation in it) and is denominated as crack growth resistance (or fracture toughness). It is determined experimentally. To carry out of these experiments new methods and materials specimen with specially initiated cracks [2, 3] were developed. It is possible to conclude about the reliability and serviceability of the material as a structural element using the data of the material crack growth resistance. It is obvious that the higher the material crack growth resistance, the higher is its reliability in operation. But the increase of crack growth resistance (making the materials more elastic) leads to the decrease of its general (macroscopic) technical breaking strength σ_t or fatigue limit (σ_{-1}). The most important task for metallurgy and the materials science lies in the optimisation of physico-mechanical properties of structural materials according to such two parameters: value of technical strength (σ_t) or fatigue limit (σ_{-1}), and the value of materials crack growth resistance (K_{IC}).

At present the maximum stress intensity factor at the crack tip K_{IC} or crack tip opening displacement δ_{Ic} at the moment of its start under the quazistatic (monotonically growing) external loading are the most widely used characteristics of the material crack growth resistance. Under the long-term constant or cyclically changed loading the material crack growth resistance is characterised by the diagram of fatigue crack growth resistance (Figure 2): $v(K_I)$ vs the stress intensity factor (K_I) near the crack tip. The threshold $K_{I\,max} = K_{Ith}$ value is established and it characterises such a stressed state of the material in the process zone (In) when for all $K_I < K_{Ith}$ the crack will not start.

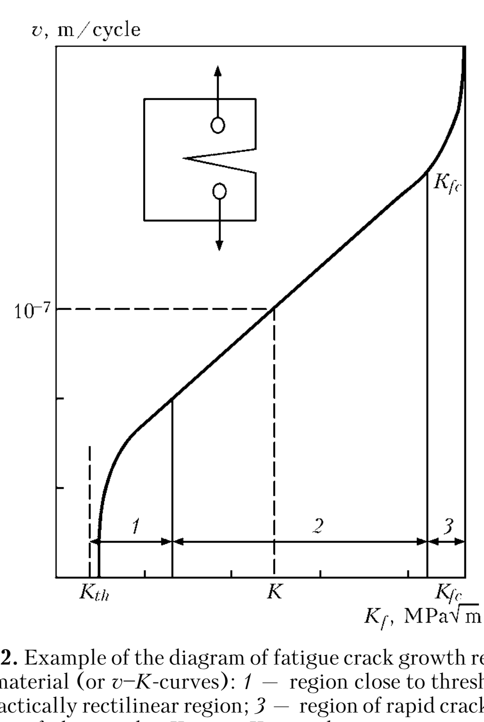

Figure 2. Example of the diagram of fatigue crack growth resistance of the material (or v–K-curves): *1* — region close to threshold K_{th}; *2* — practically rectilinear region; *3* — region of rapid crack growth and entire failure under $K_{I\,max} = K_{Ifc}$ condition

Use of crack growth resistance characteristics for assessment of welds strength. Modern engineering practice in the engineering, in the building of different objects like bridges, tunnels, dams, pipelines, object of atomic and heat power engineering, railway transport, avia- and space techniques etc. widely uses the technologies of structures connection by welding. The E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine has made a huge contribution into the development and introduction into practice of new, up-to-date technologies of structural materials joining. It is the great merit of the Institute's staff and of its scientific leader — a world known scientist B.E. Paton [4]. Scientists of this Institute, in particular V.I. Trufyakov, I.K. Pokhodnya, V.I. Makhnenko, L.M. Lobanov, V.I. Kyrian and other [5–7], have developed a number of modern methods for assessment of welded structures strength and life. Here the methods of fracture mechanics were effectively applied. Figure 3 shows the results [8] of the evaluation of physicomechanical characteristics degradation for 15Kh1MF steel of steam pipeline and joint weld metal after 190 thousand hours of exploitation by the standard characteristics and characteristics of crack growth resistance. It was established [8] that only crack growth resistance characteristic — a short-term crack growth resistance K_{IC} and the effective fatigue crack growth resistance threshold K_{th} — among all factors of mechanical state as to basic metal were sensitive to its degradation. At the same time it was established that the joint weld metal underwent the most intensively degradation during the long-term exploitation, and this degradation makes the metal of the weld the most sensitive to fracture after the long-term exploitation. In this case the impact toughness also becomes sensitive if specimen contains a rather sharp notch. It has been also revealed that the changes of mentioned above characteristics agree well corelation with fractographically determined decrease of fracture power intensity. At the same time the increase of standard elongation φ (in contrast to decrease of standard reduction of area ψ) does not testify to the increase of material elasticity but is the result of microdamageing of the weld metal. Such microdamages lead to the micro defects opening under the specimen tension and all this formally reveals in the elongation of the material.

Typical structure of the joint weld and its heat-affected zone contains always typical heterogeneities caused by technologies and materials of welding, and also by the properties of materials being welded [7]. In many cases it is faulty fusions, cracks, different structure of the HAZ material, influence of the service environments etc. When it is necessary to estimate the strength or durability of the welded structure then the methods of fracture mechanics or characteristics of the weld material crack growth resistance and HAZ are very important (see Figure 3). So, the development of the effective experimental methods for the determination of these characteristics is very important in theoretical and practical sense.

Let us consider estimation of these characteristics on the RQN601 steel welded plate [9]. In this case the

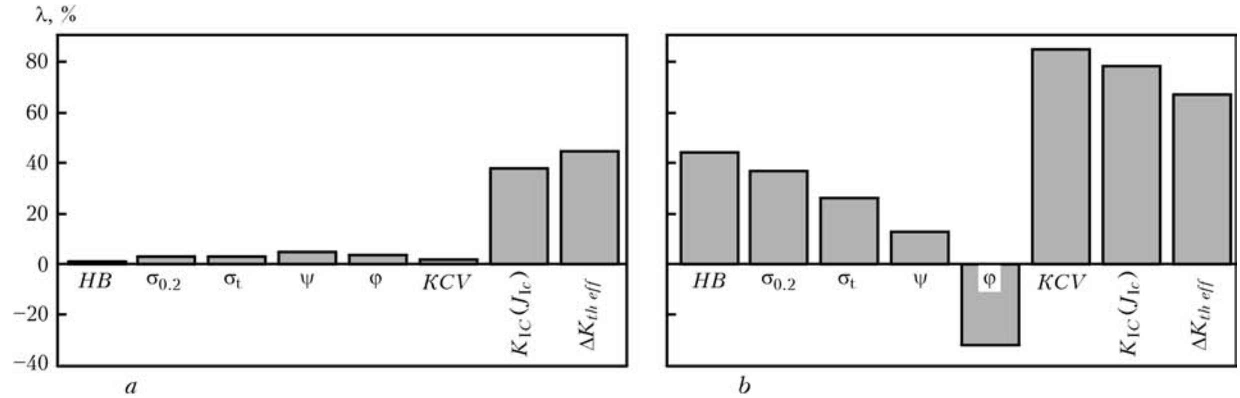

Figure 3. Decreasing λ of the mechanical properties of the 15Kh1M1F steel steam pipeline (*a*) and weld metal (*b*) after 190 ths h of exploitation at Ladyzhin thermoelectric power station $\left(\lambda = \frac{\sigma^{(0)} - \sigma^{(g)}}{\sigma^{(0)}} \cdot 100\ \%\right)$

fracture mechanics methods are used to assess the crack growth resistance of the weld zone. The scheme of the welded plate and beam specimen for crack growth resistance evaluation is shown in Figure 4, and the results of crack growth resistance δ_{Ic} determination — in Figure 5. The given experimental data (see Figure 5) on the material crack growth resistance of different zone in the weld using the COD values, that is δ_{Ic} value, show that according to this characteristic the lowest resistance to facture (to crack propagation) has the HAZ, and considerable data scattering. It must be mentioned that the procedure itself of δ_{Ic} determination for a weld is rather complicated.

All these circumstances entailed scientists, in particular scientists of the H.V. Karpenko Physico-Mechanical Institute, to develop new and more perspective methods for evaluation of crack growth resistance characteristics of structural materials including welds. One of them is the method of speckle image registration [10] of surface points near the crack tip in process zone (Figure 6). A precise analysis of material elastic-plastic deformation in the process zone of the crack plate was done in [10], D16AT alloy specimen were used. The value of displacementi $\delta_y(x)$ was measured in the process zone at different values of measuring base b (b_1, b_2, b_3), that is $\delta_{yi} = b_i + e_{yi}(x)$, $i = 1$–3. The established distribution of displacements d_p in the process zone is shown in Figure 6 where curves *1*–*3* correspond to different measuring bases b_i at $p =$ = const, and curves *1*′, *2*′, *3*′ — after unloading, correspondingly. The received results show that experimental evaluation of δ_{Ic} between the crack tip edges when the mode I macrocrack starts to propagate, can be different in dependence on the measuring base b_i. At the same time the results in Figure 6 show that the value (length) of process zone d_p is independent of the model crack growth opening evaluation base. It remains stable for the given material. This experimental fact can be used for a certain modification of the δ_c-model [1], and for a certain modified methods of evaluation of crack growth resistance characteristics δ_{Ic} for structural materials (in particular joint welds) by assessing the process zone d_p.

According to the δ_c-model [1] the d_p value for a plate with central crack of $2l_0$ length under tension

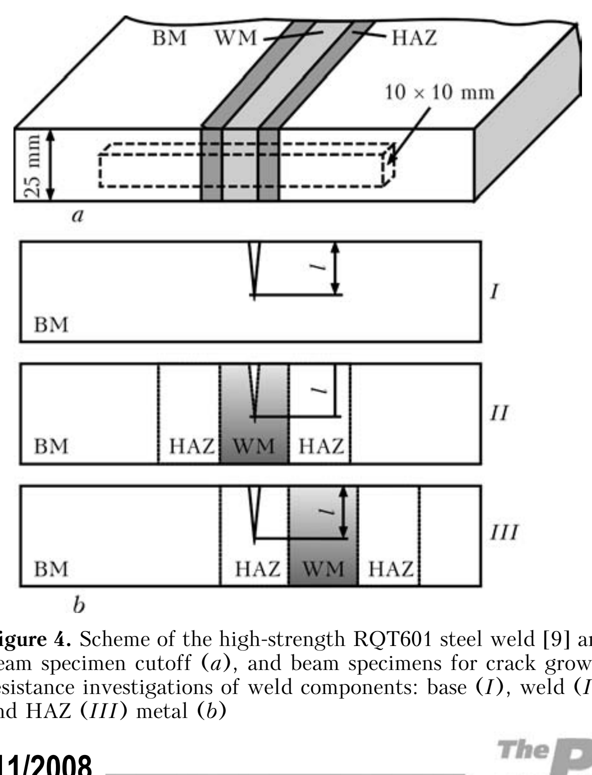

Figure 4. Scheme of the high-strength RQT601 steel weld [9] and beam specimen cutoff (*a*), and beam specimens for crack growth resistance investigations of weld components: base (*I*), weld (*II*) and HAZ (*III*) metal (*b*)

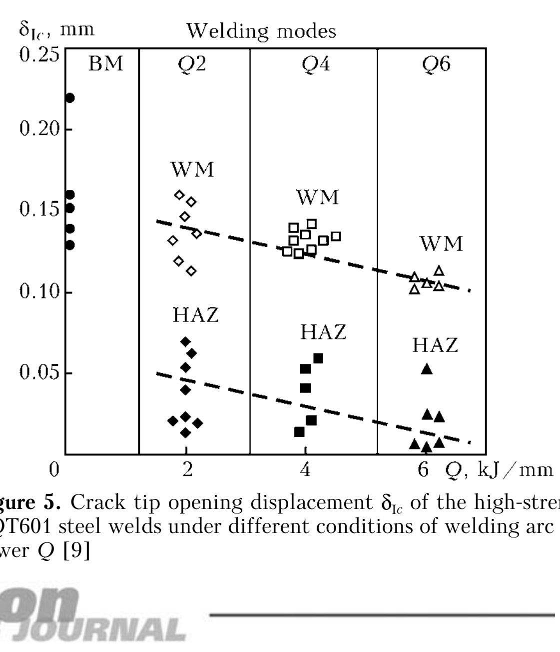

Figure 5. Crack tip opening displacement δ_{Ic} of the high-strength RQT601 steel welds under different conditions of welding arc heat power Q [9]

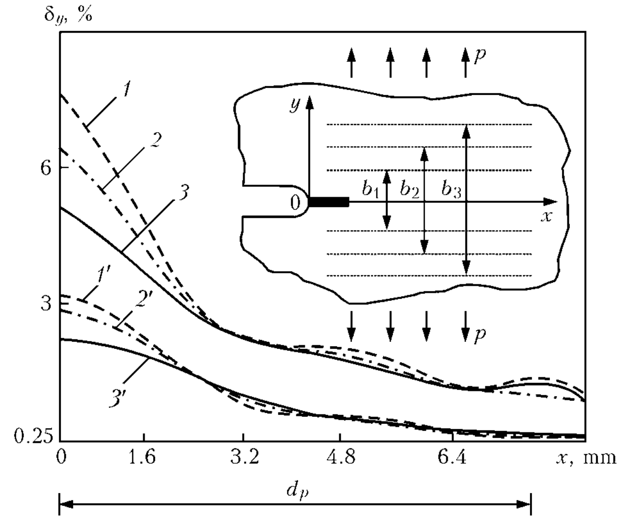

Figure 6. Distribution of displacement $\delta_x(t)$ at the crack tip under different measuring bases b: *1* — b_1 = 1.28; *2* — b_2 = 2.56; *3* — b_3 = 3.08 mm in the loaded (*1–3*) and unloaded (*1′–3′*) D16AT alloy specimen

is connected with the application of load of p intensity and averaged stress σ_0 in the process zone by the dependence:

$$d_p = l_0 \left(\sec \frac{\pi p}{2\sigma_0} - 1 \right), \qquad (2)$$

where σ_0 is the averaged stress value in the process zone. For materials being strengthened this value is determined by $\sigma_0 = \frac{1}{2} (\sigma_{0.2} + \sigma_t)$.

The $d_{p*} = d_*$ value becomes a certain characteristic of the material properties if the body with macrocrack ($2l_0$, $d_p << l_0$) is loaded by load p up to rupture. Using these results and the δ_c-model concept one can receive the following a formula for evaluation of the average $\delta_{Ic} = \delta_{Ic}$ as a deformational characteristic of crack growth resistance of structural material or the weld:

$$\delta_{Ic} = 8\sigma_0 d_*/(\pi E), \quad d_* < l_0 \qquad (3)$$

(if $d_* \sim l_0$, then this formula has a more complicated structure).

Using formula (3) for determination of δ_{Ic} one can avoid difficulties in its direct evaluation. Besides, the use of formula (3) allows determining δ_{Ic} on the base of d_* data received by metallographic analysis of macrobreaks (fracture) surfaces of different zones in the welded joint.

Use of *J*-integral for the estimation of crack growth resistance in weld of structural materials. The J-integral is being often used in engineering practice in particular when estimating the crack growth resistance of elastic structural materials. This characteristic of the structural material resistance to brittle fracture (crack propagation) in its physical sense is the value of a minimum energy, being accumulated in the unit of the material, taking into account its elastic deformation necessary for the formation of two units of free surface of this volume. Corresponding Cherepanov–Rice formulae [1, 11] were established for calculation of this energy value. But the realisation of these calculations needs the introduction of a certain rheological model of plastically deformed material volume in the process zone. So, at the end of all calculations we receive certain approximate value of this characteristic. Taking into account the complicated character of J-integral calculation (even the approximate) it is good to use the δ_c-model concept [1] of the material quazibrittle fracture for its calculations. In the frames of the δ_c-model the basic equation that relates the material crack growth resistance δ_{Ic} and the characteristic of the materials stress-stain state in the process zone, that is in the In-state region, is $2\gamma = \sigma_0\delta_{Ic}$, where γ is the density of the material surface energy, and $\sigma_0 = \frac{1}{2}(\sigma_{0.2} + \sigma_t)$ is the average stress of the material in the process zone.

Using the above mentioned we have

$$J_{Ic} = 2\gamma = \frac{1}{2}(\sigma_{0.2} + \sigma_t)\delta_{Ic}, \qquad (4)$$

where δ_{Ic} is calculated from (3). So, we have a simple engineering formula for the estimation of J-integral.

Use of fracture mechanics methods of cracked bodies for the crack growth resistance evaluation of welds in service environments. In the early 1980's a new concept concerning the physicomechanical situation at the deformed solid crack tip in the working environment was formulated by I.M. Dmytrakh, V.V. Panasyuk and L.V. Ratych [12]. The essence of this concept is as follows. The crack growth rate of the body under loading in surface-active environmens depends not only on the stress intensity factor K_I but also on the physicochemical situation of the system «environment–metal» at the crack tip (but not on the body surface). It was shown [12] that such characteristic of the system «environment–metal» near the crack tip as hydrogen index pH and electrode potential E on the metal surface, $(pH)_s$ and E_s, and at the crack tip, $(pH)_t$ and E_t, are different. Methods for $(pH)_t$ and E_t evaluation are developed in [12, 13].

Tasking into consideration the particular physicochemical situation at the crack tip in the surface-active environments the diagram of the crack growth resistance of the structural materials was proposed [12, 13] as

$$v = f(K_I, (pH)_t, E_t), \qquad (5)$$

where K_I is the stress intensity factor for the cracked body; $(pH)_t$ and E_t are the hydrogen ion exponent and electrode potential, accordingly, at the crack tip in the system «environment–metal».

In follows from equation (5) that for receiving the invariant (v–K_I) curve such conditions should be provided:

$$(pH)_t = \text{const}, \; E_t = \text{const}. \qquad (6)$$

It was also shown [12] that maximum rate (v_{max}) in the «environment–metal» system is observed only when parameters $(pH)_t$ and E_t reach their minimum values for the given system, i.e.

$$v_{max} = f(K_I, (pH)_t^{min}, E_t^{min}). \qquad (7)$$

For this concept realisation the original methods [13] for experimental determination of $(pH)_t$ and E_t parameters for the given system were developed, and they could be used, if necessary, to regulate the value of this parameters.

Such an approach became a new tool for study and assessing the effect of the surface-active and corrosion environments on strength and durability of structural materials and welds used in nuclear, shipbuilding and aviation industries. It should be noted that by using the above concept it is possible to built the fatigue crack growth resistance curve which reflects the extremal influence of the surface-active and corrosion environments on fracture processes of materials and welds in operating environments, that is to built the basic crack growth resistance curve for the material in the structure [14]. Such curves are necessary to evaluate the durability of structural elements. Figure 7 presents the experimental data [15] for different materials and weld elements used for pressure vessels. Here the basic (calculational) curves of the materials crack growth resistance are presented, where curve *4* is the envelope for all experimental data, and curve *5* is plotted according to formula (7). The comparison of these curves gives a good correlation.

The use of the fatigue crack growth resistance concept under extremal physicochemical situation at the crack tip can be useful for the assessment of welds in the systems «anticorrosion surfacing–reactor steel». Such investigations have been carried out by scientists in the H.V. Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine (Lviv) and Central Scientific and Research Institute of Structural Materials «Prometej» (St.-Petersburg, Russia) [16, 17]. These investigations were conditioned by the requirements of Finnish supervising bodies when installing the equipment for NPP in Finland.

CONCLUSIONS

1. It was shown that the crack growth resistance parameters of structural materials and welds are more sensitive to changes of physicomechanical properties of materials in structures under long-term exploitation in comparison with traditional (classical) characteristics.

2. New approaches to determination of δ_{Ic} and J_{Ic}-integral and construction of basic fatigue crack growth resistance curves for structural materials and welds are proposed, which can be used in engineering practice for assessing the serviceability of structural elements of long-term operation in the given environment, and also for the determination of their residual life.

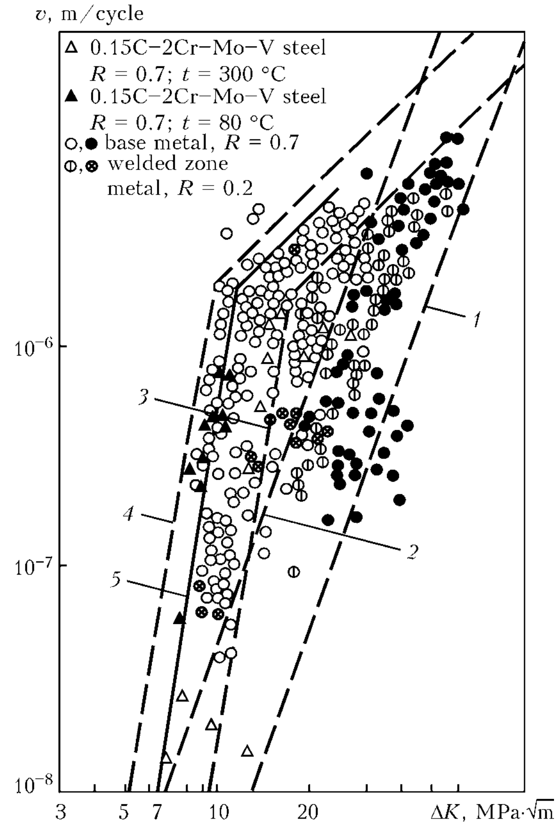

Figure 7. Fatigue cyclic crack growth resistance diagram (v–K curves) for pressure vessel metal: *1, 2* — according to ASME test method; *3, 4* — according to Bamford [15] (generalised experimental data); *5* — basic diagram in the frames of the proposed concept

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NEW DEVELOPMENTS TO OVERCOME COLD CRACKING IN WELDED MARTENSITIC CREEP-RESISTANT STEELS

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HAZ of a new steel grade of the system 9Cr–3W–3Co–V–Nb with controlled adding of boron and nitrogen was investigated using physical simulation of a weld. After the complete thermal cycle of welding the size of grains of primary austenite and structure of lath martensite are identical to those in initial state. The suppression of fine-grained HAZ formation shows high potential of a new steel as for the reduce of tendency of joints towards cold cracks formation.

Keywords: *martensitic steels, creep damage, cold cracking*

Within the last decades several projects in Japan, the USA and Europe focused on the development of new ferritic/martensitic steel grades for high temperature applications in thermal power generation [1–4]. The second big task was the improvement of existing creep-resistant chromium steels. Ferritic/martensitic grades are favoured for thick walled components because of their good thermo-physical properties compared to austenitic grades or Ni-based superalloys [5, 6]. As a result of the increased research activities, several creep-resistant martensitic steels like P91, P92, E911 or P122 have been standardised and are already in service for up to 10 years in power stations all over the globe.

Arc welding is the major joining and repair technology for power plant components. Long-term results of cross-weld creep tests as well as in-service experience over several years have identified the narrow HAZ of weldments as a weak point during creep exposure. The 100 ths h creep strength of welded structures at service temperature is sometimes reduced by as much as 50 % compared to the creep strength of the base material [7–9]. The fine-grained region of the HAZ, which is exposed to peak temperatures just above A_{c_3}-transformation temperature (completed austenitisation) during welding, is most susceptible to creep cracking. This type of cracking is categorised according a scheme set up by Schuller et al. [10] as Type IV cracking. Good overviews on Type IV cracking are given by Middleton and Metcalfe (1990), Ellis and Viswanathan (1998) and Francis et al. (2006) [11–13]. Up to today, Type IV cracking is seen as the major end-of-life failure mode in welded structures of ferritic/martensitic steels.

Within this work, a martensitic 9 % Cr steel test melt is investigated concerning creep strength and the formation of its HAZ and implications on the long-term creep strength of weldments.

Experimental. A 20 kg test melt (NPM1) of a 9Cr–3W–3Co–V, Nb, B, N steel was produced by vacuum induction melting. The chemical composition of the melt NPM1 is following basic research work on 9Cr–3W–3Co–V, Nb steels performed by Abe et al. [14] at the National Institute for Materials Science in Japan. The boron content was set to 120 ppm and the nitrogen content to 130 ppm. This special boron–nitrogen balance should promote the formation of finely dispersed nitrogen-rich MX particles but still inhibit the formation of large boron–nitrides. The exact chemical composition as follows, wt.%: 0.074 C; 0.29 Si; 0.44 Mn; 0.009 P; 0.004 S; < 0.005 Al; 9.26 Cr; 0.06 Ni; 2.84 W; 2.95 Co; 0.21 V; 0.056 Nb; < 0.005 Ti; 0.012 B; 0.013 N. For homogenisation,

Table 1. Parameters of the quality heat treatment of test melt NPM1

Heat treatment	Heating rate, $°C \cdot h^{-1}$	Temperature, °C	Duration, h	Cooling media
Austenitising	250	1150	1	Air
Tempering	250	770	4	Same

Table 2. Parameters of GTA welding of NPM1 test weld

Run	Welding process	Diameter of filler material, mm	Current, A	Voltage, V	Welding speed, $cm \cdot min^{-1}$	Type of current/polarity
1	GTAW 141	2.0	100	11.0	8	DCRP
2–3	GTAW 141	2.0	165–180	12.5–13.5	8–12	Same
4–32	GTAW 141	2.4	180–190	12.5–13.5	8–12	»

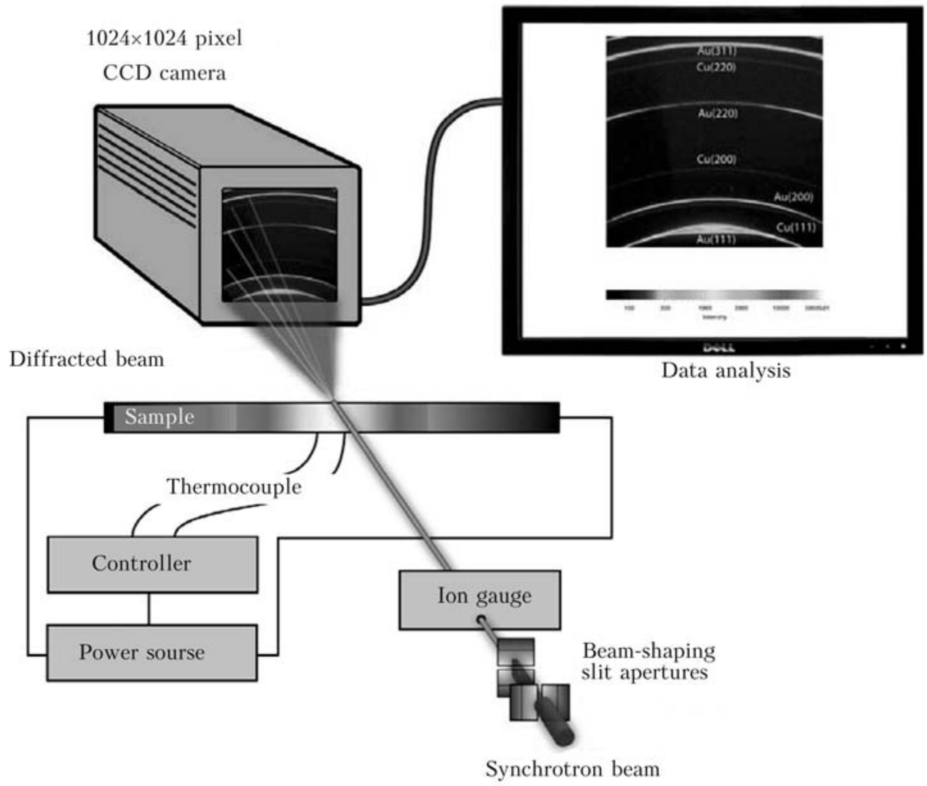

Figure 1. Schematic of experimental setup for the in-situ XRD experiments using advanced photon source (J. Elmer)

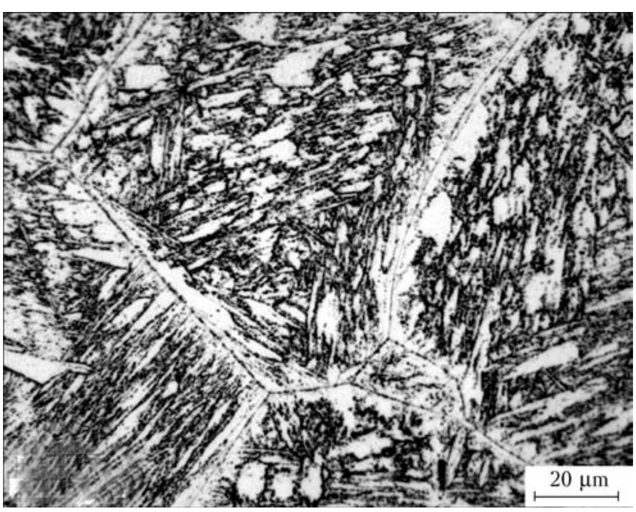

Figure 2. Optical micrograph of NPM1 base material

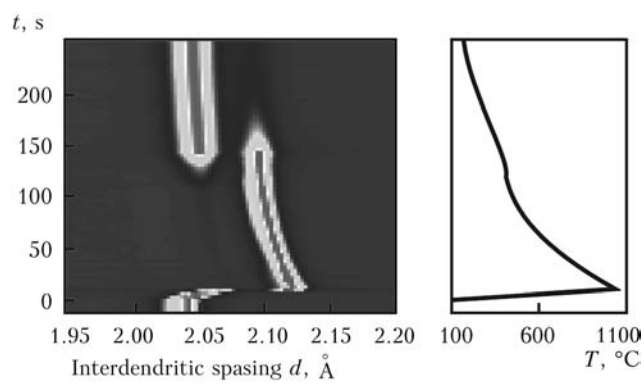

Figure 3. Phase transformations in steel NPM1 during characteristic welding thermal cycle. Complete austenitisation at heating is followed by martensitic transformation at cooling (*d* values: tempered martensite of ~2.03; austenite of ~2.13; martensite of ~2.05 Å)

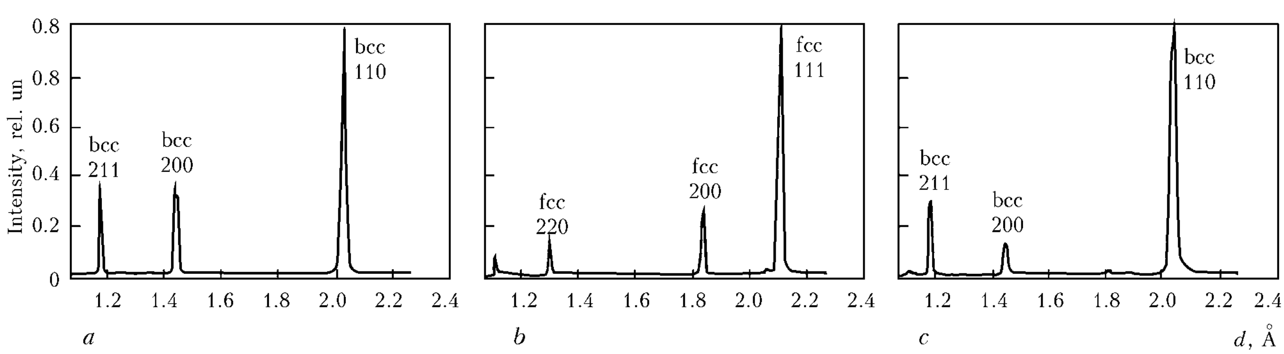

Figure 4. X-ray diffraction spectra at different temperatures during simulated welding thermal cycles. Starting at room temperature from a ferritic microstructure (*a* — bcc-peaks), at 1048 °C only austenite is present (*b* — fcc-peaks), after the completed welding thermal cycle at 27 °C bcc-peaks characterise the newly formed martensitic microstructure (*c*)

the NPM1 ingot was re-forged before a quality heat treatment consisting of austenitising at 1150 °C for 1 h and tempering at 770 °C for 4 h (Table 1).

Optical microscopy was used to characterise the base material and HAZ microstructure. Physical HAZ simulation was performed using a Gleeble thermo-mechanical simulator. The applied welding thermal cycles were characterised by fast heating to a peak temperature of either 1100 or 1200 °C and a characteristic cooling time of $t_{8/5}$ = 22 s ($t_{8/5}$ is the cooling time between 800 and 500 °C). Microstructural investigations have been performed on the identical location before and after HAZ simulation. Therefore, the designated area was marked by hardness indentations and

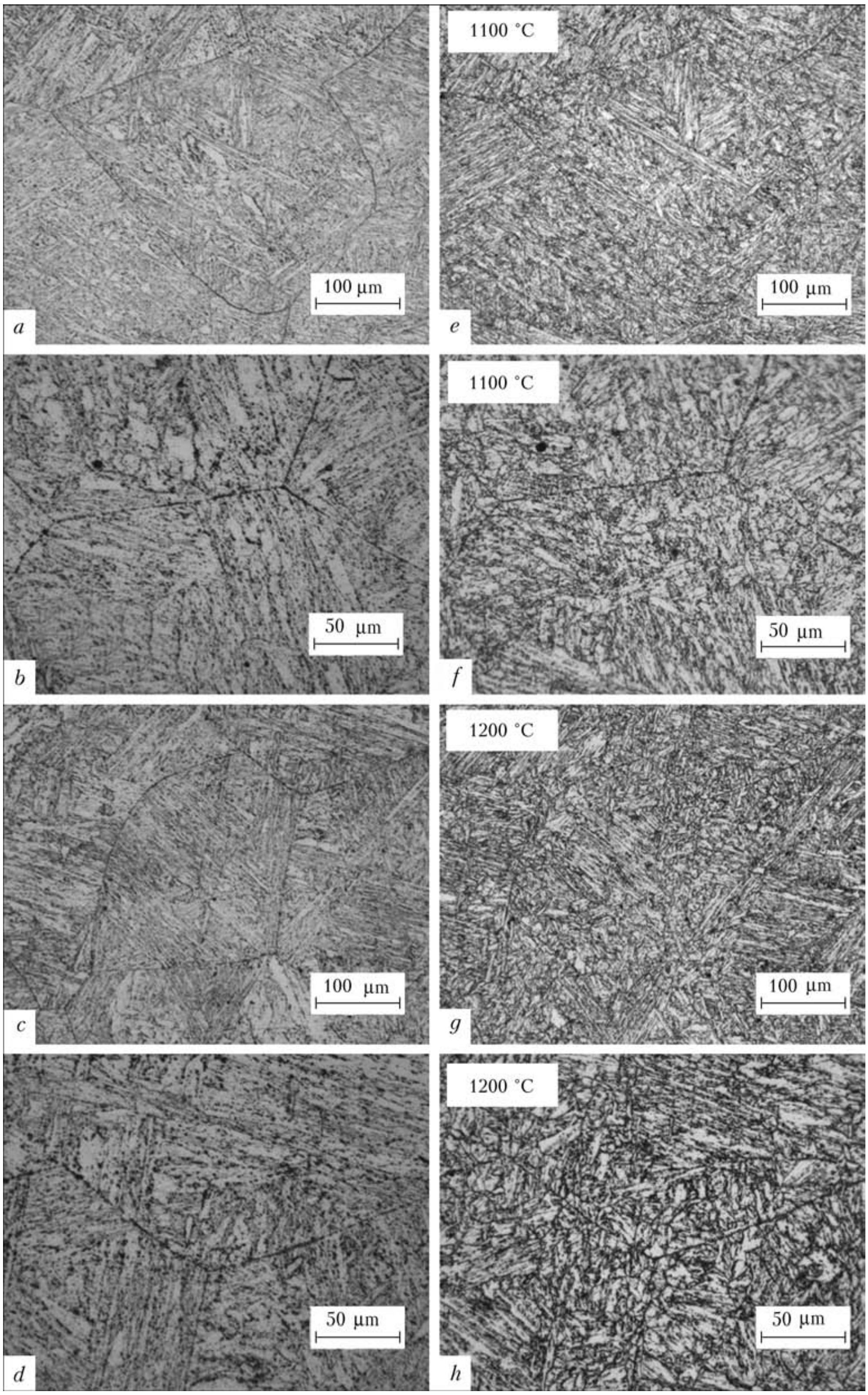

Figure 5. Microstructural changes in steel NPM1 after welding test sample (*a*–*d*) and physical HAZ simulation (*e*–*h*)

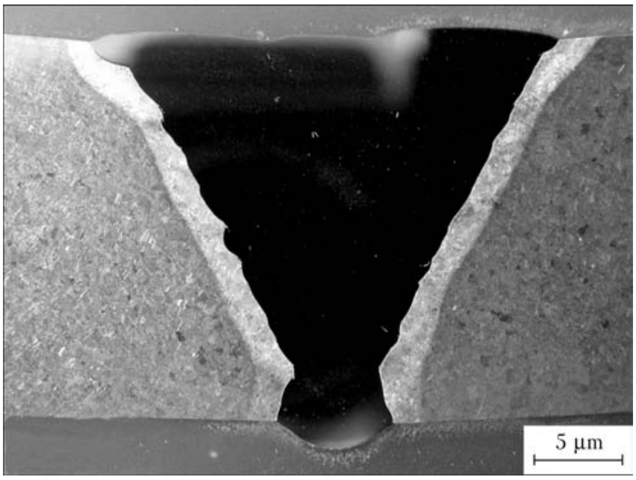

Figure 6. Macrograph of NPM1 test weld fabricated with nickel-base filler metal

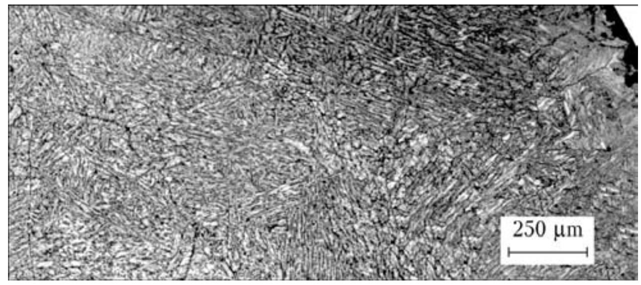

Figure 7. Grain structure in the HAZ of NPM1 test weld. The fusion line is located on the right side of the image. No distinct formation of a grain-refined zone is observed

HAZ simulation was performed in argon atmosphere to prevent oxidation of the specimen surface area.

Phase transformations during characteristic welding thermal cycle have been studied by in-situ X-ray diffraction using high energetic synchrotron radiation. This method was adopted to steels by J. Elmer. A description of this method as well as of the experimental setup (Figure 1) is given in detail in [15–17]. The applied welding thermal cycle was intended to result in a complete grain refinement characterised by a heating rate of 100 $K \cdot s^{-1}$ up to a peak temperature of 1100 °C and a characteristic cooling time of $t_{8/5} =$ = 40 s.

To verify results of the Gleeble HAZ simulation, a TIG weld was produced using a Ni-based filler metal (Nibas 70/20-IG). Details of the welding process are summarised in Table 2. The post-weld heat treatment was carried out at 740 °C for 4 h.

Results and discussion. NPM1 base material shows a tempered martensitic microstructure (Figure 2). Precipitates along the prior austenite grain boundaries as well as the martensitic lath boundaries have been identified as chromium-rich carbides and vanadium-niobium-rich carbo-nitrides. The homogeneous microstructure is characterised by an average grain size of 250 μm.

Monitoring phase transformations during the welding thermal cycle by in-situ XRD showed the complete austenitisation of the bcc (body-centered-cubic) tempered martensite and formation of virgin martensite on cooling. Figure 3 shows the sequence of phase transformations during heating to a peak temperature of 1100 °C and subsequent cooling.

The XRD spectrum recorded at a temperature of 1048 °C shows only fcc (face-centered-cubic) peaks of the austenite phase (Figure 4). Therefore it can be stated that the 1100 °C welding thermal cycle fully austenitised the steel. On cooling, martensitic transformation started at a temperature of 430 °C.

While in a conventional ferritic/martensitic steel grade heating up to a peak temperature of 1100 °C leads to a complete refinement of the grain structure, NPM1 reveals a different behaviour. The original prior austenite grains, observed in the base material, can be seen also after the HAZ simulation. Figure 5 shows a comparison of NPM1 microstructures before and after weld simulation with peak temperatures of 1100 and 1200 °C. Not only the prior austenite grains are preserved throughout the simulation also the major part of martensite laths and lath packages can be found after the weld simulation in their initial appearance. This is an extraordinary behaviour of NPM1 steel as it was shown earlier that the steel undergoes two full phase transformations during the simulated welding thermal cycles. Although some formation of fine grains was observed close to the initial prior austenite grain boundaries no complete grain refinement was observed.

Similar behaviour was observed for the NPM1 test weld. The welding procedure resulted in the formation of an approximately 2 mm wide HAZ (Figure 6). A micrograph of the HAZ of the test welded joint, shown in Figure 7, reveals no homogeneous fine-grained region throughout the entire HAZ.

Summary and discussion. A bar of a new 9Cr–3W–3Co–V, Nb test melt with a balanced boron-nitrogen relation was successfully produced by vacuum induction melting and forging. NPM1 shows a tempered martensitic microstructure with precipitates along prior austenite grain boundaries and martensite lath boundaries. The average grain size is 250 μm. Phase transformations during characteristic welding thermal cycles were observed by in-situ X-ray diffraction using synchrotron radiation. At a temperature of 1100 °C the steel was shown to be fully austenitic. Despite the transformations during the thermal cycle the microstructure is almost not changed by the welding thermal cycle. Prior austenite grains and packages of martensite laths from the initial microstructure are preserved. Also the test weld produced by TIG welding showed no homogeneous fine-grained zone formation in the HAZ.

As Type IV cracking in martensitic steels is strictly limited to the fine-grained region of the HAZ, this steel grade has high potential to overcome Type IV cracking. For cross-welds of NPM1, a significant improvement of creep strength is expected and for validation long-term creep tests are currently performed.

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port with the synchrotron experiments. Many thanks to Dr. Fujio Abe of NIMS and his team for valuable discussions. This work was funded by the Austrian research promotion agency (FFG), which is gratefully acknowledged.

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WHAT IS NEW WITH THE ISO STANDARD 3834:2005?

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The contribution deals with the relation between the standards ISO 3834:2005, ISO 9000:2000 and ISO 9001:2000, explains the changes related to the version ISO 3834:1994, the extension of its applicability, and their connection with the European Directives. Moreover, it lists the requirements on manufacturers of welded products, and mentions the possibility of combined (harmonised) certification for the use in different regions of the world.

Keywords: *welding, welded products, quality assurance, requirements on manufacturers, standard, certification*

In many companies (particularly in those which manufacture, maintain or repair investment goods), welding is the most important technology for the joining of metals. The quality of the whole product and thus its service capability, reliability and safety are dependent on the quality of the welded joint in a variety of aspects. If welded products are relevant to safety in the most countries of the world, laws, decrees and regulations exist with minimum requirements on such products, which are very often laid down in standards, international or national ones. In the European Union in a lot of European Product Directives in the European Union, a link is made to ISO or EN standards. Related to the field of welding, ISO 3834:2005 is the standard defining the requirements on manufacturers. The same can be done in other regions of the world, where other laws or decrees exist.

Technical significance of welding in modern production. Since the beginning of the so-called industrial age in the middle of the 19th century, the signifi-cance of joining (i.e. the connection of metallic materials) has increased continuously. Although not only welding as so-called forge welding but also brazing and soldering had been known for centuries, riveting was initially used almost exclusively for non-detachable joints in addition to bolting and screwing for detachable joints not only in mechanical engineering but also in structural steel and plant engineering.

With the invention and further development firstly of oxyacetylene welding and subsequently of arc welding as well, these two processes have increasingly superseded riveting in the metal-fabricating industry and in structural steel engineering since the start of the 1930s. The reason for this was that, instead of the lap joints necessary for riveting, it was possible to manufacture butt joints which led, on the one hand, to weight savings and, on the other hand, to greater leak tightness of the components and to better force flux.

The high technical significance of welding becomes particularly evident whenever welding must be carried out on essential components or even on components relevant to safety. This is because, as a rule, the result of the welding cannot be proven at all, completely or at an economically justifiable expense. In the international standard ISO 9000, such fabrication processes are designated as «special processes». In addition to the measures which are required of the manufacturing companies in the pertinent sets of rules and standards for safety reasons in order to prove the product quality, there is thus also a demand for particular proof in the quality management system of the companies which manufacture these products, trade with them, operate them or are otherwise responsible for handling them.

Quality assurance in welding technology. *Quality assurance in welding shops*. With the publication of the first edition of ISO 9000 ff. in 1987, the International Organisation for Standardisation (ISO) stipulated requirements on quality management systems in a cross-sectoral form for the first time. With the revision of ISO 9000 series in the year 2000 the standards ISO 9002 and ISO 9003 were withdrawn. Since then, there has been only one level for the certification of a quality management system on the basis of ISO 9001. The requirements of ISO 9000 ff. do not include any technical specifications on the shops. However, the standard ISO 9000:2005 [1] indicates the following in Point 3.4.1:

«Note 3. A process where the conformity (3.6.1) of the resulting product (3.4.2) cannot be readily or economically verified is frequently referred to as a «special process».

For companies, this entails that the following quite particularly applies to the manufacture of products with so-called «special processes» according to ISO 9001, Point 4.1 [2]:

«The organisation (i.e. the manufacturing company) shall

a) identify the processes needed for the quality management system and their application throughout the organisation (see 1.2);

b) determine the sequence and interaction of these processes;

c) determine criteria and methods needed to ensure that both the operation and control of these processes are effective;

d) ensure the availability of resources and information necessary to support the operation and monitoring of these processes;

e) monitor, measure and analyse these processes and;

f) implement actions necessary to achieve planned results and continual improvement of these processes.

These processes shall be managed by the organisation in accordance with the requirements of this international standard.

Where an organisation chooses to outsource any process that affects product conformity with requirements, the organisation shall ensure control over such processes. Control of such out-sourced processes shall be identified within the quality management system».

So that not every company must now start from scratch with the development of its own system for quality assurance in welding technology and in order to make such systems comparable, ISO has, for almost 20 years, therefore been endeavouring to stipulate, in a harmonised form extending across different products in one standard, those requirements on welding shops which are relevant to quality. The basis for this standard was the document IIW Doc. 902 86 [3] which had already been published in the International Institute of Welding (IIW) in 1986 with the title «Guideline for quality assurance in welding technology» and in which the nine most important quality factors are named and methods of guaranteeing them are described.

Accordingly, the quality factors are: design of weldments; materials; welding processes; welding personnel; weld edge preparation; workmanship; postweld heat treatment; testing and inspection.

In the international standard ISO 3834:2005, requirements on the manufacturing welding shops with regard to these quality factors are stipulated in the following objectives (see Part 1 [4]):

• to lay down quality requirements for welding production in shops as well as on sites; to describe suitable requirements on manufacturers, which use welding in production; to assure, the means to guarantee the applicability to all kinds of constructions by graduated requirements; to present instructions for the description of the manufacturers' capability to produce welded constructions in the defined quality;

• to prepare requirements for rules and contracts;

• to describe the manufacturers' management welding requirements for a Quality Management System.

The standard still offers three levels in Parts 2–4, after the revision of ISO 9000 ff. in the year 2000, this standard now presents only one level according to ISO 9001:2000.

The three levels of ISO 3834 are: comprehensive quality requirements in Part 2 (ISO 3834 2 [5]), standard quality requirements in Part 3 (ISO 3834 3 [6]) and elementary quality requirements in Part 4 (ISO 3834-4 [7]). These requirements are listed and compared in Table 1 of Part 1 (see below).

The ISO standards which are quoted in Parts 1 to 4 and can be replaced by other, technically equivalent regional standards — that is new — are listed in Part 5 [8]. Because Paragraph 2.1 in ISO 3834-5:2005 may be misunderstood, the responsible subcommittee 4 of CEN TC121 has proposed the following change in the first chapter: «Conforming to the quality requirements of ISO 3834-2, ISO 3834-3 or ISO 3834-4, this shall be claimed by a manufacturer in accordance with one or more of the following options:

a) adoption of the ISO documents listed in 2.2;

b) adoption of other documents that provide technically equivalent conditions to the ISO documents listed in 2.2;

c) adoption of different supporting standards where these are required in application standards used by the manufacturers».

There is no change in Paragraph 2 of Clause 2.1.

Remarks about the selection of the requirement level or of the Part 2, 3 or 4 of this standard to be applied are given in ISO 3834-1. More detailed information is given in the new Part 6 of ISO 3834 which is published as a technical report ISO TR 3834-6:2007 [9] and in a publication in the ISO Forum [10].

Certification according to ISO 3834 been customary in Europe and other parts of the world for many years and, in a lot of cases, serves to authorise the company for welding work in the so-called regulated fields [11].

Quality assurance on welded products. As a rule, the proof of the quality of products relevant to safety is regulated in laws or statutory instruments [11], in Europe increasingly in European Directives, e.g. the Construction Product Directive (CPD) or the Pressure Equipment Directive (PED) (Table) [11]. These directives refer to so-called product standards if these are available, e.g. to EN 1090 «Execution of steel and aluminium structures» [12], EN 13445 «Unfired pressure vessels» [13], EN 13480 «Metallic industrial piping» [14] or EN 15085 «Welding of railway vehicles and components» [15]. With regard to the requirements on the welding shops which manufacture, maintain or repair these products, these product standards generally refer to the European standard EN 729 which is identical with the standard ISO 3834 whose requirements are thus applicable.

If no statutory demands exist, the contracting parties can, of course, agree upon the requirements of the standard ISO 3834.

If there are no such agreements either, the manufacturer of welded products is, depending on the significance, value and safety relevance of the product, well-advised to make a specification for the level to be fulfilled according to ISO 3834 and to prove this to an independent certifier. In any case, it should fulfil, as a minimum, the elementary quality requirements according to ISO 3834 4:2005.

European Product Directives relevant to welding activities: 87/404/EEC — Simple Pressure Vessel Directive (SPVD); 97/23/EC — Pressure Equipment Directive (PED); 99/36/EC — Transportable Pressure Equipment Directive (TPED); 89/106/EEC — Construction Product Directive (CPD); 01/16/EC — Conventional Rail System Di-

Summary comparison of ISO 3834, Parts 2 to 4: Helpful criteria for selecting the appropriate part of ISO 3834

Criteria	ISO 3834-2	ISO 3834-3	ISO 3834-4
Requirements review	Review required		
	Record is required	Record may be required	Record is not required
Technical review	Review is required	Record may be required	Record is not required
	Record is required		
Subcontracting	Treat like a manufacturer for the specific subcontracted product, services and/or activities, however final responsibility for quality remains with the manufacturer		
Welders and welding operators	Qualification is required		
Welding co-ordination personnel	Required		No specific requirement
Inspection and testing personnel	Qualification is required		
Production and testing equipment	Suitable and available as required for preparation, process execution, testing, transport, lifting in combination with safety equipment and protective clothes		
Equipment maintenance	Required to provide, maintain and achieve product conformity		No specific requirement
	Documented plans and records are required	Records are recommended	
Description of equipment	List is required		Same
Production planning	Required		»
	Documented plans and records are required	Documented plans and records are recommended	
Welding procedure specifications	Required		»
Qualification of the welding procedures	Required		»
Batch testing of consumables	If required		»
Storage and handling of welding consumables	A procedure is required in accordance with supplier recommendations		In accordance with supplier recommendations
Storage of parent material	Protection required from influence by environment; identification shall be maintained through storage		No specific requirement
Post-weld heat treatment	Confirmation that the requirements according to product standard or specifications are fulfilled		No specific requirement
	Procedure, record and traceability of the record to the product are required	Procedure and record are required	
Inspection and testing before, during and after welding	Required		If required
Non-conformance and corrective actions	Measures of control are implemented procedures for repair and/or rectification are required		Measures of control are implemented
Calibration or validation of measuring, inspection and testing equipment	Required	If required	No specific requirement
Identification during process	If required		No specific requirement
Traceability	Same		
Quality records	»		

Tank manufacturing shop

rective (CRSD); 96/48/EC — High Speed Rail Directive (HSRD).

Combined certification. On the basis of the new revision of ISO 3834:2005, it is now generally possible to certify a manufacturer in one audit process valid in different regions of the world if the authorised certification bodies work closely together. Such a process is now successfully under way between the Russian certification organisation NAKS and the German certification organisation DVS ZERT and was practised at the company «Komzomolets» in Tambov, Russia (Figure).

Summary. The new version of ISO 3834:2005 constitutes a standard which deals with requirements on welding shops and, with its three levels, can be applied all over the world and in all the relevant sectors. All the sets of rules and standards relating to welded products can refer to it. The newly introduced Part 5 allows the combination with other regional sets of standards in welding technology.

1. *ISO 9000:2005*: Quality management systems — Fundamentals and vocabulary.
2. *ISO 9001:2000*: Quality management systems — Requirements.
3. *IIW Doc. 902–86*: Guideline for quality assurance in welding technology. IIW, 1986.
4. *ISO 3834-1:2005*: Quality requirements for fusion welding of metallic materials. Part 1: Criteria for the selection of the appropriate level of quality requirements.
5. *ISO 3834-2:2005*: Quality requirements for fusion welding of metallic materials. Part 2: Comprehensive quality requirements.
6. *ISO 3834-3:2005*: Quality requirements for fusion welding of metallic materials. Part 3: Standard quality requirements.
7. *ISO 3834-4:2005*: Quality requirements for fusion welding of metallic materials. Part 4: Elementary quality requirements.
8. *ISO 3834-5:2005*: Quality requirements for fusion welding of metallic materials. Part 5: Documents with which it is necessary to conform to claim conformity to the quality requirements of ISO 3834-2, ISO 3834-3 or ISO 3834-4.
9. *ISO/TR 3834-6:2006*: Quality requirements for fusion welding of metallic materials. Part 6: Guidance on implementing ISO 3834.
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12. *EN 1090*: Execution of steel and aluminium structures.
13. *EN 13445*: Unfired pressure vessels.
14. *EN 13480*: Metallic industrial piping.
15. *EN 15085*: Welding of railway vehicles and components.

MECHANICAL DIMENSIONAL EFFECTS IN TWO-PHASE INORGANIC MATERIALS

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Extremums of strength, ductility and hardness of two-phase metallic and non-metallic materials containing nano- and microsized phases were established experimentally. It is shown that the ductility maximum, minimums of strength and hardness are characteristic of materials under the condition of equality of mean grain size D and mean free distance (mean free path) between the second phase particles Λ, i.e. at $D = \Lambda$. Maximums of strength and hardness are achieved when the mean free path Λ is equal to the mean distance between particles λ, i.e. $\Lambda = \lambda$. In microlaminate materials the dimensional effects are manifested at values of alternating layer thickness below 1–2 μm. An interrelation is established between the specific surface of the interphases and extreme values of mechanical properties of two-phase materials.

Keywords: *mechanical property, dimensional effects, electron beam technology*

Strength, hardness and ductility are characteristic examples of structurally-sensitive properties of inorganic materials. In single-phase polycrystalline materials grain size is one of the main structural parameters, controlling the mechanical properties.

Dependence of plastic flow stress σ_y in such materials on grain size D is described by the known Hall–Patch relationship

$$\sigma_y = \sigma_x + kD^{-1/2}, \qquad (1)$$

where σ_x and k are some coefficients; D is the mean grain size.

In two-phase systems the number of structural parameters increases and structure–property dependences become more complicated.

Figure 1 schematically represents the main structural elements and parameters of their spatial distribution: mean grain size of the equiaxed grain or mean width of columnar crystallites D; mean diameter of spherical (or close to spherical) second phase particles d; mean free distance between the particles (mean free path) Λ; mean distance between particles λ.

Parameter Λ has a simple geometrical meaning, whereas various approaches can be used at λ description: mean distance between particles or closest particles in an arbitrary slip plane or volume [1–3]

$$\Lambda = \frac{2}{3}\frac{d}{f}(1 - f), \qquad (2)$$

where f is the volume fraction of second phase particles. If $f << 1$, then

$$\Lambda = \frac{2}{3}\frac{d}{f}. \qquad (3)$$

Specific surface of grain boundaries, for grains of a cubic shape, is equal to

$$S_b = \frac{3}{D}. \qquad (4)$$

Specific interface of particles is equal to

$$S_{int} = \frac{6f}{d}. \qquad (5)$$

Quantitative studies of the structure and mechanical properties of two-phase metallic, metal-ceramic and ceramic massive condensates (thick films) produced by electron beam evaporation and subsequent condensation of different materials in vacuum, allowed detecting the characteristic dimensional effects and more precisely defining some traditional concepts of structure–mechanical properties dependences. This concerns, primarily, the strength and ductility of two-phase materials with micro- and nano-sized structural elements.

In two-phase condensed materials free distance Λ and grain size D decrease with increase of volume fraction of second phase particles f. Therefore, the following structural conditions can be in place in the two-phase condensate structure: $D < \Lambda$, $D > \Lambda$, $D = \Lambda$.

At $D < \Lambda$, achieved at a small amount of relatively large second phase particles, Hall–Patch relationship is valid. At $D > \Lambda$ dispersion-strengthened condensates containing nano-sized particles of the hard high-modulus second phase, demonstrate an increase of strength

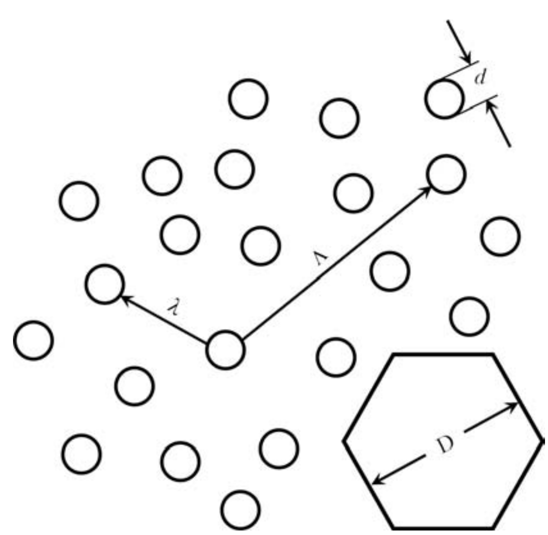

Figure 1. Elements of two-phase material structure

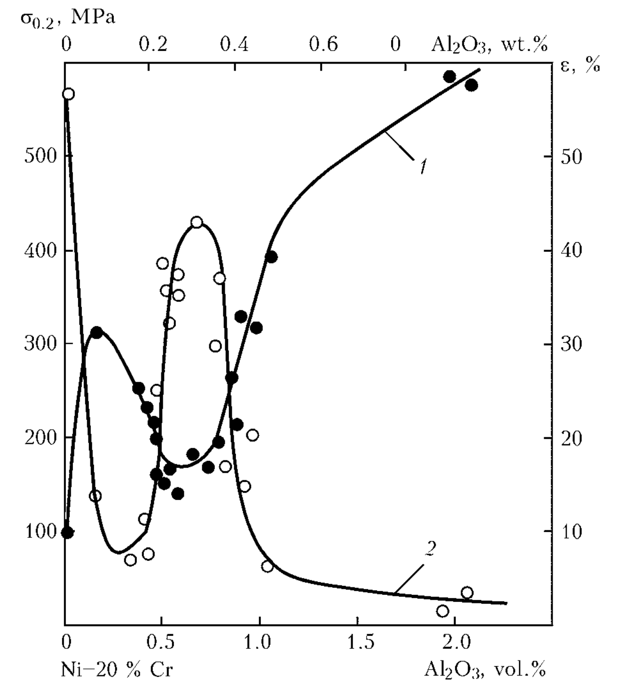

Figure 2. Mechanical properties at 20 °C of Ni–20 wt.% Cr condensates depending on Al_2O_3 content: *1* — yield point $\sigma_{0.2}$; *2* — elongation at fracture ε

at increase of their volume fraction and shortening of distance λ or Λ between them [4]:

$$\sigma_y = \sigma_0 + \frac{\alpha_x G_m b_m}{L}, \qquad (6)$$

where σ_0, G_m, b_m are the yield point, shear modulus and Burgers vector of dislocations of a matrix containing second phase particles, respectively; L — is the linear value respectively equal to λ or Λ; α_x are the some coefficients at which Orowan relationship is valid.

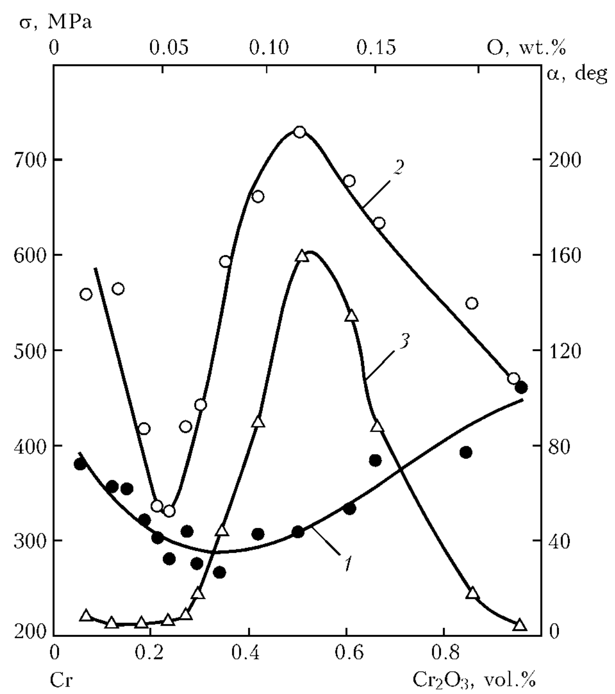

Figure 3. Mechanical properties of $Cr-Cr_2O_3$ condensates of 1.0–1.2 mm thickness at 20 °C: *1* — yield point $\sigma_{0.2}$; *2* — tensile strength σ_t; *3* — angle of bending to fracture α

At $D = \Lambda$ characteristic extremums of mechanical property values appear on structure–property concentrational dependencies.

These dimensional effects were first reported in 1975 for the case of ductility maximum of two-phase Fe–NbC and $W-ZrO_2$ condensates [5]. Figure 2 shows the dependencies of yield point $\sigma_{0.2}$ and elongation ε at fracture of two-phase Ni–20 wt.% Cr + Al_2O_3 condensates of approximately 1 mm thickness deposited at T_s = 900 °C. Mean crystallite size D of condensates of pure solid solution of Ni–20 wt.% Cr is equal to 60 μm. At addition of 0.14 vol.% Al_2O_3 it decreases to 10 μm and at 0.63 vol.% Al_2O_3 it is equal to 4 μm. Mean particle diameter d at 0.63 vol.% Al_2O_3 is equal to 40 nm. Thus, structural condition $D = \Lambda$ is fulfilled in the range of 0.50–0.85 vol.% Al_2O_3 and, accordingly, a clear elongation maximum ε and yield point minimum $\sigma_{0.2}$ are present on concentrational dependences of mechanical properties. Microhardness is also minimum in this narrow range of second phase concentrations. Dislocation structure forming at tension of these samples, is considered in [6]. Mechanical property extremums at $D = \Lambda$ are characteristic of both ductile metal matrices, and brittle metal (Be, Cr, Mo, W) and ceramic matrices [6–8]. As an example, $Cr-Cr_2O_3$ condensates deposited at T_s = 970 °C and containing (0.5 ± 0.1) vol.% Cr_2O_3 demonstrate a clear ductility maximum (bending angle of flat samples equal to 160°) and lowering of the yield point (Figure 3). Microhardness is also minimal in this range of Cr_2O_3 concentrations.

Dependences of mechanical properties with minimum $\sigma_{0.2}$ values and maximum ductility were also obtained at investigation of two-phase condensates based on iron and nickel with nanoparticles of low-modulus materials, namely $Fe-Ce_2S_3$, $Fe-CaF_2$ [6] and Ni–C [9].

It should be specially noted that structural condition $D \approx \Lambda$ can be also achieved with other methods of treatment of inorganic materials with dispersed particles of the second phase. In studies [10, 11] it is shown that addition of optimum quantities of active additives (modifiers) to iron melts, which refine the grain and non-metallic inclusions of cast steel and result in formation of $D \approx \Lambda$ structure, is accompanied by increase of ductile properties of the castings.

The second extremum of mechanical properties was found in two-phase condensates containing 60–80 vol.% of dispersed phases with a higher modulus of elasticity (shear) compared to the matrix. In such structures the mean free path between particles Λ is approximately equal to mean distance between particles λ, i.e. the second structural condition $\Lambda = \lambda$ is satisfied. Second phase volume fraction for this condition can be estimated based on the assumption that in the volume [1]

$$\lambda = \sqrt{\frac{2}{3f}}\, d(1 - f). \qquad (7)$$

Equating this expression to the above expression for Λ, we obtain $f \approx 0.66$.

It should be noted that when $\Lambda = \lambda$ the relationship $\Lambda = \lambda \approx 0.34d$ is valid.

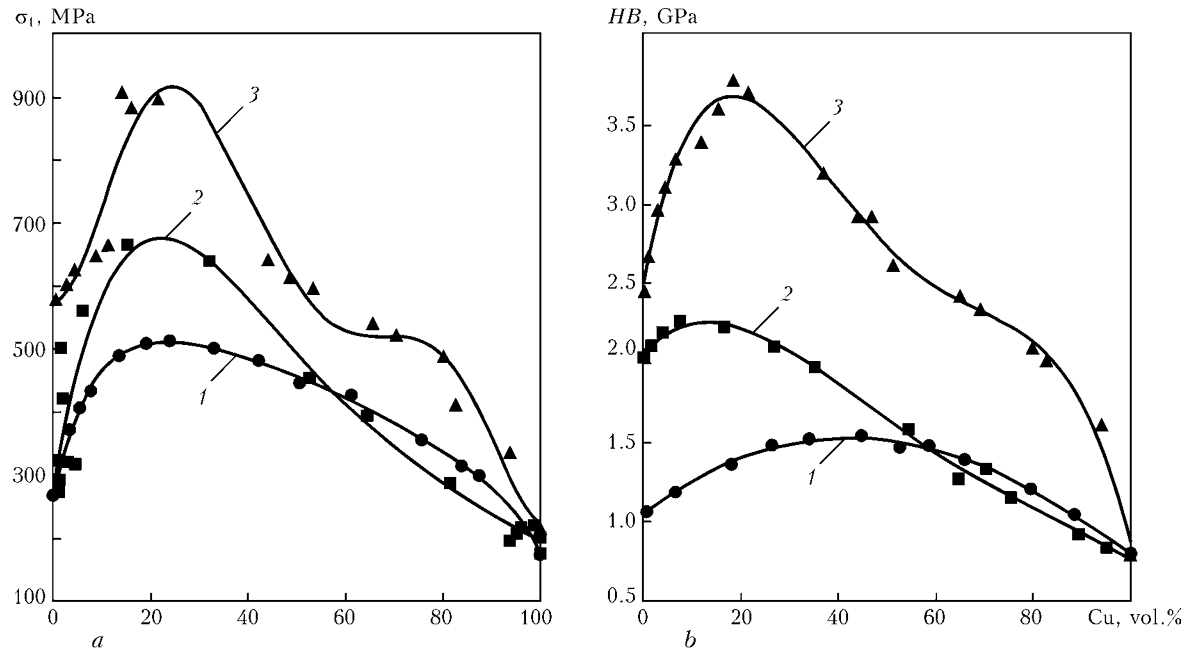

Figure 4. Mechanical properties at 20 °C of two-phase Fe–Cu (*1*), Cr–Cu (*2*) and Mo–Cu (*3*) condensates depending on copper content: *a* — tensile strength σ_t; *b* — microhardness *HB*

Figure 4, *a, b* gives the characteristic maximums of strength and microhardness of two-phase Fe–Cu, Cr–Cu and Mo–Cu condensates produced by deposition of components from two independent sources at substrate temperatures T_s equal to 600, 850 and 950 °C, respectively. Condensate thicknesses were equal to 0.8–1.2 mm. Mean values for Mo, Cr, Fe grains in the respective condensates at 20 vol.% Cu are equal to approximately 1 μm, the width of copper interlayers between then being ~ 0.3 μm. Yield point of such two-phase condensates in the above concentration interval can be assessed applying the following expression:

$$\sigma_{0.2} = \sigma_{0.1} + \frac{20 G_1 b_1}{d_1} f_1, \qquad (8)$$

where $\sigma_{0.1}$, G_1, b_1, f_1 and d_1 are the yield point, shear modulus, Burgers vector, volume fraction and size of particles of high-modulus second phase, respectively.

As follows from the presented dependencies, strength and hardness of two-phase condensates with a high-modulus matrix (Fe, Cr, Mo) increase at addition of low-modulus second phase (Cu), which does not agree with the known rule of additivity (rule of mixtures) applicable to similar but coarse-grained two-phase materials.

Ductility and fracture toughness of these condensates depend, primarily, on individual properties of the high-modulus phase, as well as on its dimensions, shape and spatial distribution in the volume. Coalescence of individual grains with formation of skeleton crystal forms markedly lowers the level of the above properties.

Such maximums of strength were obtained at investigation of TiC–Ti, TiC–Mo and Be–Al condensates [12]. Maximums of strength and fracture toughness in the range of 60–80 vol.% of the high-modulus phase were also demonstrated for the cases of two-phase TiB_2–ZrO_2, Al_2O_3–ZrC materials produced by sintering dispersed powders [13, 14].

Strength maximum of a classic sintered hard WC–Co cermet containing approximately 60–63 vol.% WC [7], as well as hardness maximum of 36–38 GPa (established by us in nano-structured B_4C–Ti condensate with 10–20 vol.% Ti) and hardness maximum of 38–40 GPa in an ion-deposited nano-structured TiN–Si_3N_4 film with 15–20 at.% Si_3N_4 [15], can be a further confirmation of the general nature of the above-mentioned structural condition $\Lambda = \lambda$.

Mechanical dimensional effects are also characteristic of a wide class of multilayered materials produced by electron beam evaporation of initial inorganic materials. The interfaces between the layers are known to be

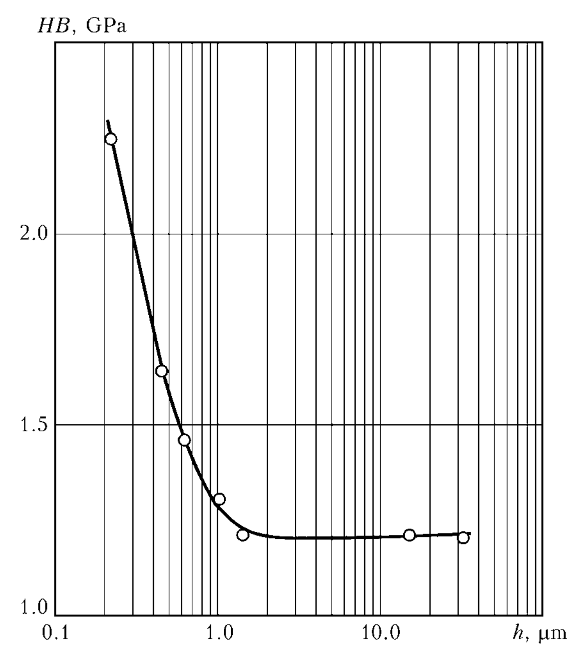

Figure 5. Microhardness *HB* of Fe–Cu microlayered condensates depending on thickness *h* of alternating layers

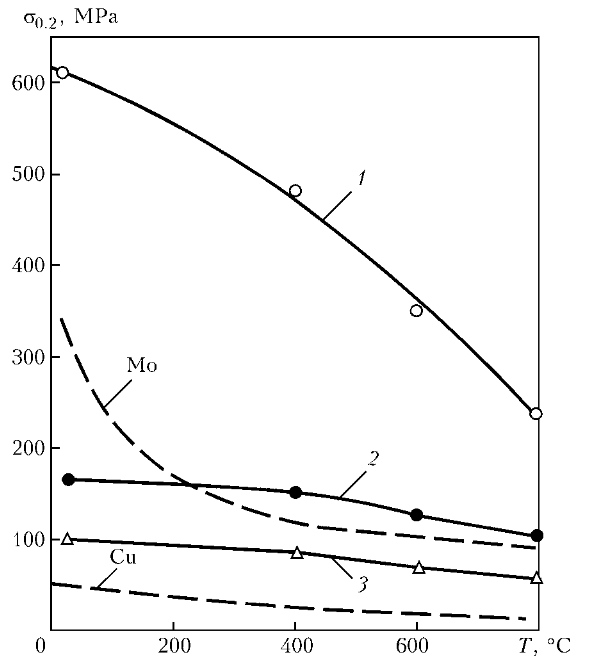

Figure 6. Yield point of Mo–Cu condensates depending on microlayer thickness: *1* — Mo 1.1 μm, Cu 1.8 μm thick; *2* — Mo 1.1 μm, Cu 7.0 μm thick

sources of long-range internal stresses and effective barriers in the path of moving dislocations. Therefore, multilayer materials can be high-strength ones at room temperature and high-temperature resistant at high temperatures. Layers thicknesses are one of the main parameters determining their properties.

Figure 5 shows the dependence of microhardness *HB* of bulk Fe/Cu condensates with alternating microlayers of iron and copper of the same thickness *h*. An abrupt increase of condensate microhardness is observed at layer thicknesses below 1–2 μm. Strength properties of multilayer condensates increase in a similar fashion. Investigations of mechanical properties of Fe/Cu, Cr/Cu and Mo/Cu microlaminate condensates with equal thickness of the layers showed that the interrelation of yield point with layer thicknesses can be presented by the following dependence:

$$\sigma_{0.2} = \sigma_0 + \frac{15G\,b}{h}, \qquad (9)$$

where $\sigma_{0.2}$, G and b are the yield point, shear modulus and Burgers vector of the crystalline lattice of high-modulus (load-carrying) layer of Fe, Cr or Mo, respectively. For instance, for Fe/Cu with G_{Fe} = = 81 GPa, b_{Fe} =0.248 nm, h = 0.5 μm and σ_0 = = 150 MPa, yield point will be equal to 750 MPa. The steady-state creep rate of Fe/Cu condensate with equal thickness of the layers at 600 °C and 60 MPa stress is 100 times lower than that of pure iron.

Figure 6 shows the temperature dependence of the yield point of bulk microlayered Mo–Cu condensates with two variants of alternating Mo and Cu microlayers.

Mechanical properties of microlayered Ni16Cr5Al–10 vol.% NbC and Ni6Al12Mo–23 vol.% Mo at 20 °C exceed, and at 1000 °C are close to mechanical property values of high-temperature nickel alloy JS6L [12]. It is anticipated that in the near future new super high temperature-resistant multilayered materials of the type of cermet–oxide, carbide–boride, etc. will be obtained by evaporation and condensation of inorganic materials.

CONCLUSION

1. The considered extremums of mechanical properties of two-phase inorganic materials are functionally related to specific surface of grain boundaries and specific surface of the interphases.

2. $D = \Lambda$ is a condition of equality of $S_b = S_{int}$, that can be readily confirmed by equating dependencies (4) and (5) allowing for dependence (3).

3. $\Lambda = \lambda$ is a condition of achievement of the maximum specific interface of the second high-modulus phase S_{int}, as from dependencies (3) and (5) $S_{int} \sim$ $\sim 1/\Lambda$. Λ value is minimum when $\Lambda = \lambda$. The interphase is known to be an effective barrier in the path of moving dislocations.

4. Laminated structures, consisting of alternating dissimilar layers of the same thickness, demonstrate dimensional effects of strength and ductility at layer thickness below 1–2 μm. Similar to two-phase discrete structures, addition of a low-modulus layer leads to strength increase.

5. The above regularities allow a more purpose-oriented «engineering» of the structure and programming the properties of new materials.

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PLASMA NANOPOWDER METALLURGY

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Generalized are the results of many years of research aimed at development of physico-chemical fundamentals and optimum design-technological realization of the processes of plasma nanopowder metallurgy, ensuring the production of a wide range of powders of the nanosized elements and compounds to produce on their basis nanostructured functional and structural materials with special properties. The main directions are determined in the path of application of the produced nanopowders and commercialization of the developed processes of plasma nanopowder metallurgy.

Keywords: *thermal plasma, reduction, plasma-chemical synthesis, nanopowders, powder metallurgy, nanostructured composites and coatings, hard alloys, nanotoxicity*

According to a number of well-grounded predictions, nanotechnologies and products and systems developed on their basis will be one of the main factors, determining the advance of science and technology in the third millennium. The interest to nanodispersed materials, including nanodispersed powders of metals and chemical compounds, is natural. Plasmachemical technology is one of the most promising processes of producing a wide range of nanosized powders of metals and compounds. Interaction of thermal plasma with the treated material ensures melting, evaporation, thermal decomposition, reduction and synthesis for practically any refractory and difficult-to-evaporate materials with producing by controllable condensation the dispersed product with particle size on the nanometer level (right down to the dimensions of a critical nuclei or cluster).

Special properties of the produced highly dispersed media determine the fields of their possible application: metal ceramics, compacting activators, additives to lubrication oils, colouring agents, modifiers of metals and alloys, and catalysts. Producing powders by the action of reactive thermal plasma (usually, the reduction and synthesis process) can be implemented as a plasma jet process, the block diagram of which is given in Figure 1 for production of powders in the thermal plasma of the arc discharge.

Such processes as plasma-hydrogen reduction and plasma synthesis in reactive media can be performed by a simple schematic of direct-flow reactor coaxially attached to the outlet nozzle of the plasma generator. In addition to a relative simplicity of process organization, they feature a high efficiency, sufficient ease of organization of a continuous process by a cycle closed by the gaseous reagent and, therefore, ecologically perfect capability of control and automation. The plasma-jet processes of dispersed material processing are (largely owing to the research of the RAS IMMS staff) among the best supported by fundamental research and advanced in terms of practical implementation [1–9].

In keeping with the methodology accepted by us, for theoretical analysis of plasma-metallurgical processes [2, 5] after determination of the system state by diagnostics or a priori assumptions, the possibility of considering the system as a quasi-equilibrium one is assumed. The result of the conducted thermodynamic calculations is determination of an equilibrium optimum of the studied process by composition and yield of the target and byproducts, and power consumption.

Studying the kinetics of plasma-jet processes is based on the postulates of the general theory of interaction of gaseous reagents with the material at different aggregate state of the latter, which was developed by us. For processes of interaction of thermal plasma with the dispersed material distributed in it, the postulate of chemical transformation limitation by the processes of transition into the vapour-gas phase is formulated. Achievement of homogenizing is the main requirement to correct organization of the plasma-jet process. Therefore, our efforts were aimed at development of mathematical models and experimental methods ensuring the mixing of dispersed raw materials with the plasma heat carrier, uniform distribution of the raw material in the high-temperature zone, optimization of the processes of heat mass transfer, de-

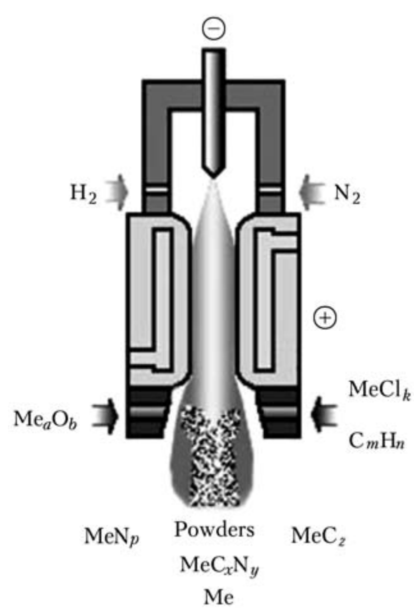

Figure 1. Block-diagram of plasma-jet technology of producing nanopowders of elements and compounds

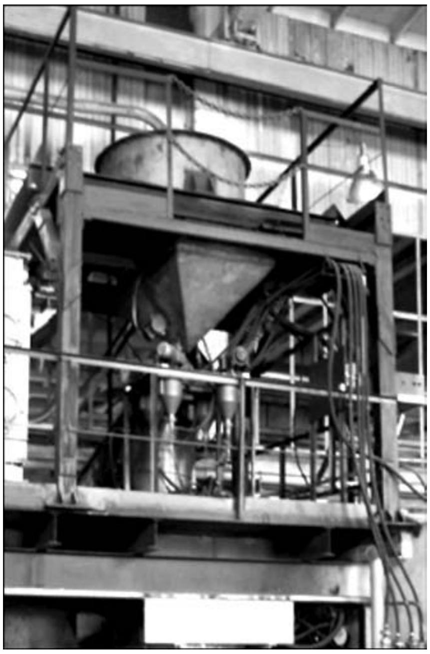

Figure 2. Commercial plasma unit of 250 kW power for producing ultradispersed tungsten powders

termining the kinetics of reagent transition into the gas phase, subsequent chemical transformations and formation during condensation.

Lately special attention has been given to the design-technological realization of plasma processes, as with correct selection of the initial materials and target product, the optimum design-technological realization ensures production of dispersed nanosystems while meeting the requirements of ecology and power and resource saving. This postulate was confirmed in practice in the plasma processes accepted by industry, for instance, technology of plasma-hydrogen reduction of refractory metal oxides (Figure 2).

On the whole, it may be stated that the fundamentals have been established of plasma nanopowder metallurgy as a promising field of science and technology, quite well supported by fundamental research and applied developments, enabling the required scaling-up in case of the necessary demand for the nanostructured structural and functional materials produced by plasma nanotechnology.

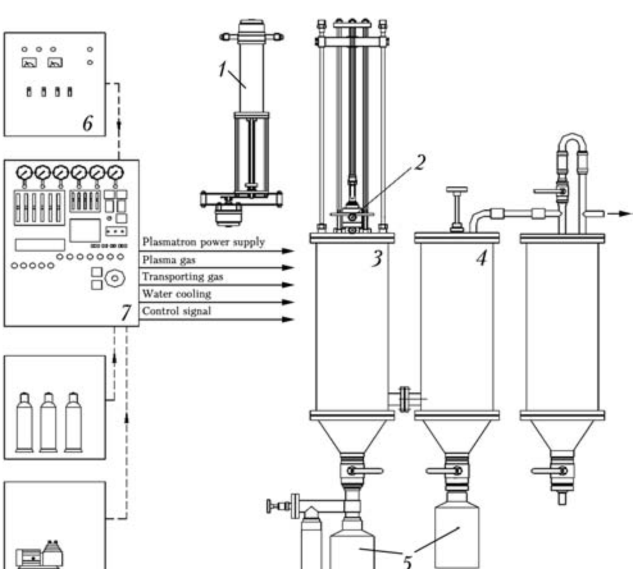

Figure 3. Schematic of an experimental plasma unit: *1* — powder feeder; *2* — plasmatron; *3* — reactor; *4* — filter; *5* — nanopowder collector; *6* — power source; *7* — CI

Physical chemistry and technology of a wide range of nanopowders of elements and compounds (metals, oxides, nitrides, carbides and carbonitrides) were optimized using the developed experimental and pilot plasma equipment (Figure 3). Figure 4 gives the characteristics of some of the produced nanopowders.

A number of promising directions of application of nanopowders of plasma reduction and synthesis was determined, in particular, for production of nanoceramic hard alloys and cutting tools with increased performance on their basis, creation of effective coatings, modifying casting alloys, etc.

Theoretical and experimental investigations of the influence of various factors on the specific surface and dispersity of nanopowders allowed determination of the possibility of controlling the average size of particles in the processes of plasma reduction and synthesis. Possibility of controlling the dispersity of powders obtained at condensation of thermal plasma flows, in particular, to produce powders with less than 1—30 nm particle sizes, was also confirmed when studying plasma chemical synthesis of oxides in oxidizing media. The determinant role of dispersed raw material and plasma gas consumption, gas flow enthalpy is revealed, and the influence of gas quenching on the size of forming particles while using the intensity of cold gas bleeding as a controlling factor, was evaluated. With the appropriate organization of quenching of the outflows it is possible to produce dispersed media on the level of cluster systems with unique properties. Figure 5 demonstrates the possibility of controlling the dispersity alongside achievement of nanosizes of the order of 5 nm in the case of plasma reduction of tungsten.

Considerable attention has recently been given to synthesis in thermal plasma, containing hydrocarbons, including production of tungsten—carbon nanocompositions, which at subsequent treatment are transformed into nanostructured tungsten monocarbide, and then into tungsten carbide—cobalt system, used to produce hard alloys with essentially higher mechanical and service properties, which are the basis for development of a wide range of highly efficient cutting tools for various applications. An ingenious multifunctional plasma unit was developed for optimization and further development of plasma synthesis processes and manufacturing test batches. The main design elements of the unit envisage the possibility of the required scaling up under the conditions of commercial production of nanosystems with compliance to ecological requirements in combination with power and resource saving.

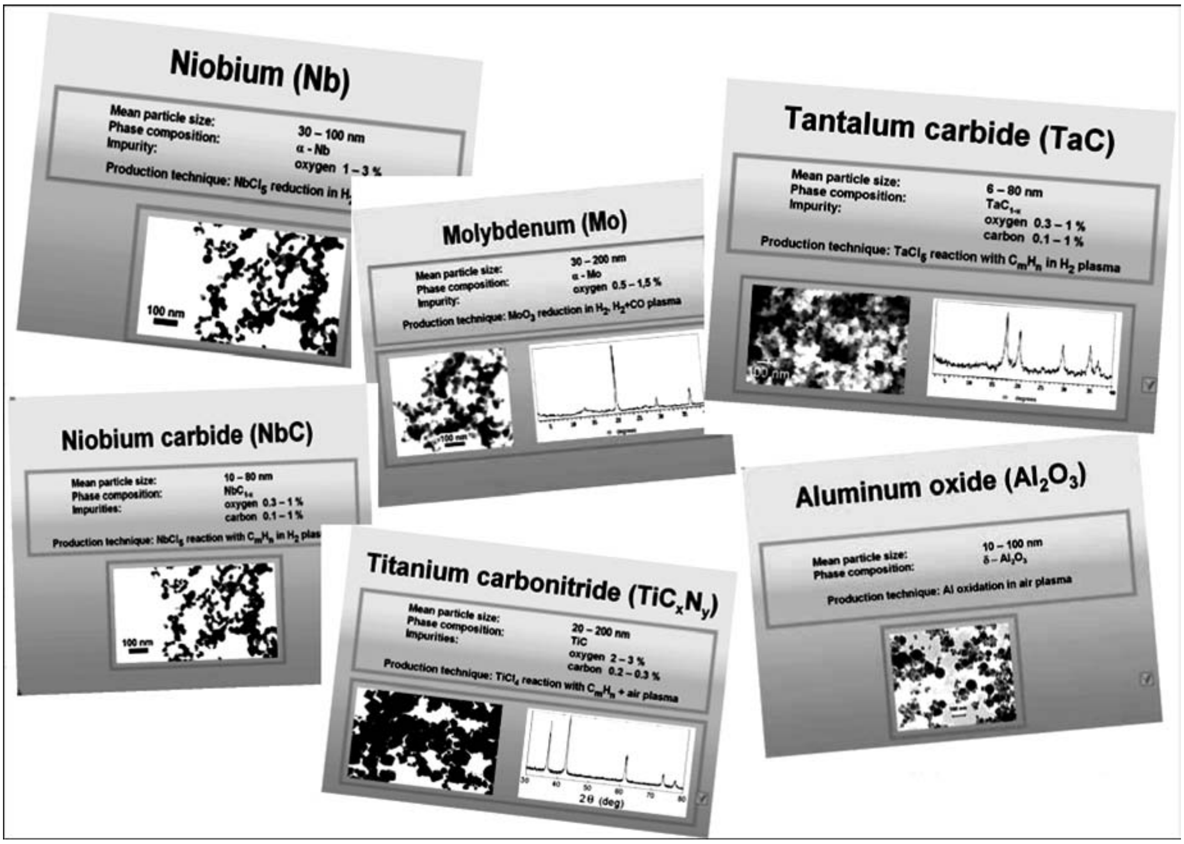

Figure 4. Characteristics of typical samples of plasma synthesis nanopowders

The basic equipment-technological diagram of production of a new range of cutting tools based on nanostructured hard alloys is given in Figure 6.

Among the promising directions of application of ultradispersed powders of plasma synthesis in composite materials science, which were confirmed in practice, note their application in development of dispersion-strengthened and superhard materials, metal-ceramic materials, structural ceramics, electrodeposited composite materials with special properties.

Note also practical application of nanopowders of refractory compounds, produced by plasma-chemical

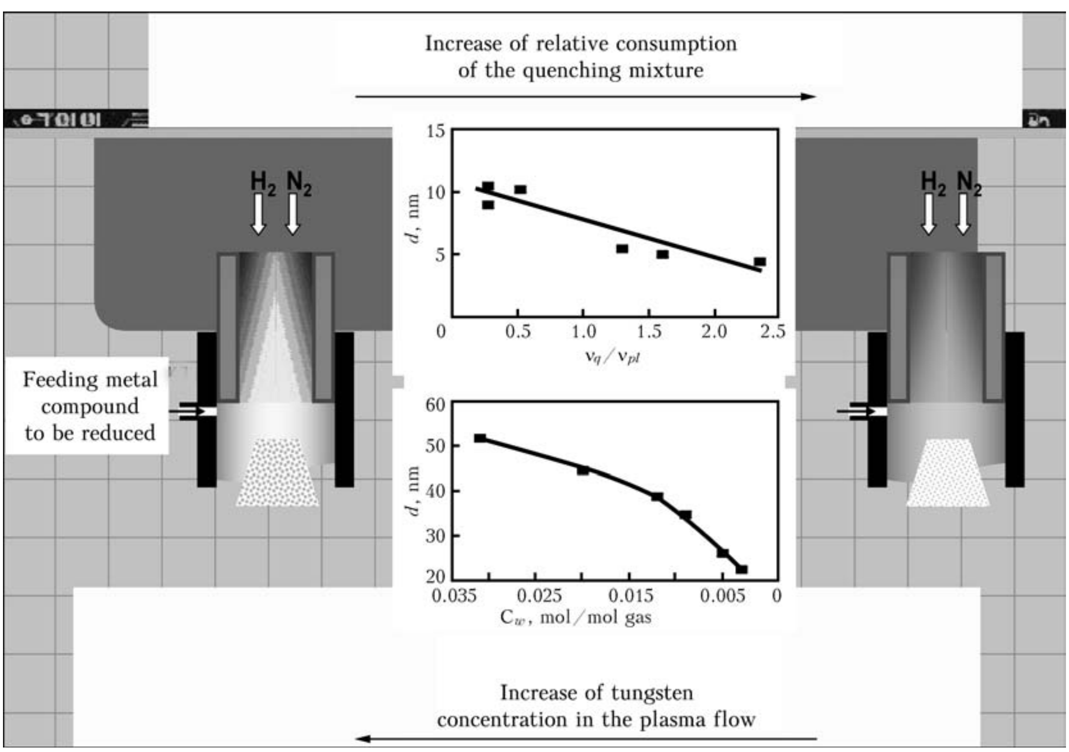

Figure 5. Control of dispersity of the produced nanopowders

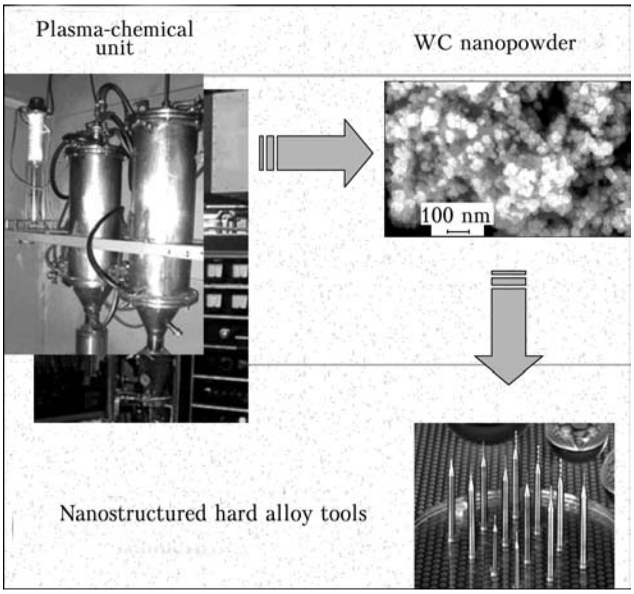

Figure 6. Hardware-technological schematic of production of tools based on nanostructured hard alloys

methods as modifiers of metals and alloys. The main prerequisites for application of nanopowders are small dimensions of the particles, commensurate with the dimensions of the nucleation centers, high sedimentation stability of particles in the melts, and possibility of achievement of a high countable concentration of particles at their low weight fraction. Application of ultradispersed particles of refractory compounds as modifiers of metals and alloys in foundry opens up the possibility of controlling the casting structure in an earlier outlined direction, allowing an impact on the grain shape and size, distribution and amount of the carbide, intermetallic and other phases. At low costs, compared to the traditional alloying methods, the technology of modification by nanopowders allows simultaneous improvement of the cast metal strength and ductility. An essential change of the alloy structure as a result of modification leads to improvement of the performance — tensile strength by 10–30 %, ductility by 1.5–2 times, endurance limit by 25–40 %. Technology of modification by nanopowders was tested on aluminium and nickel alloys, high-manganese steel, high-chromium cast irons, corrosion-resistant steels.

Considered are the possibilities of application of vacuum engineering in commercial production of nanostructured hard alloys for cutting tools. So, it is intended to perform compacting of plasma synthesis nanopowders in vacuum-compression furnaces. Strength of hard alloys, sintered in vacuum-compression furnaces, is increased as a result of both reduction of porosity and certain influence of pressure at a high temperature on the structural component of the phases and interlayers in the alloy.

A considerable reserve for improvement of the performance of hard alloy tools is application of nanocomposite coatings on its surface by the vacuum-plasma method. Unlike the alternative methods of formation of nanocomposite coatings (for instance, magnetron sputtering), the vacuum-plasma process ensures the highest deposition rates and allows quite easy control of the formed condensate properties and producing practically any complex-alloyed compositions. The nanocomposite coatings not only ensure the high microhardness of the tool surface layer and low degree of its interaction with the material being treated, but also improve its toughness. A special area of research, which should be conducted up to implementation of the industrial processes, is creation of conditions, providing the safety of the researchers and manufacturers against the possible adverse effect of the produced nanomaterials on biological objects. Purpose-oriented research, which, unfortunately, still does not get sufficient understanding and government support, is conducted by us together with the medical toxicologists, in order to develop not only highly efficient, but also ecologically safe and bio-compatible nanotechnologies.

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TWO EXAMPLES OF MATHEMATICAL MODELLING IN THE FIELD OF SPECIAL ELECTROMETALLURGY: REMELTING PROCESSES AND METAL NITRIDING

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A continuous research in the field of special electrometallurgy was carried out in France during the last 20 years, and numerical models of remelting processes (ESR or VAR) have been developed. In close collaboration with the E.O. Paton Electric Welding Institute a theoretical (i.e. modelling) and experimental study of the nitriding process of a Ni–20 % Cr alloy was performed.

Keywords: *vacuum arc remelting, consumable electrode, nickel alloy, fine-grain structure of ingot, nitriding, denitriding, levitated droplet method, digital simulation, heat transfer, material transport*

Remelting processes. Consumable electrode remelting processes have been developed to produce high-performance alloys dedicated to critical applications, for which high metallurgical quality ingots are necessary. Consequently, primary melting is not sufficient and remelting provides valuable advantages such as a fine grain structure, limited occurrence of solidification defects, low level of micro- and macrosegregation and good soundness of ingots.

The principle of the vacuum arc remelting (VAR) process (Figure 1, *a*) consists in melting a consumable metallic electrode of the required grade under a high vacuum, in order to obtain a sound ingot of good structural quality. During remelting, an electric arc is maintained between the tip of the electrode (which acts as the cathode) and the top of the secondary ingot, in order to ensure melting of the electrode. Liquid metal falls through the arc plasma and progressively builds up the ingot, which solidifies in contact with a water-cooled copper crucible. In the case of electroslag remelting (ESR), an alternating current is passed from the electrode to the water-cooled baseplate through a high-resistive calcium fluoride-based slag, thus generating Joule heating. The energy is both transferred to the electrode for the melting and to the secondary ingot. Molten metal is produced in the form of droplets which fall and build up the secondary ingot (Figure 1, *b*). Insulation from air and chemical refining, due to the presence of slag, improve the inclusional quality [1]. In both cases, during a remelting, the ingot is composed of a liquid metal pool, mushy zone and solidified part.

Remelted materials are special steels and nickel-based superalloys. Vacuum arc remelting also represents the final stage in the melting cycle of reactive metals, such as zirconium and titanium. The strategic importance of these products and their very high added value make it essential to acquire a detailed understanding of the melting processes. Mathematical modelling is a valuable tool to enhance fundamental un-

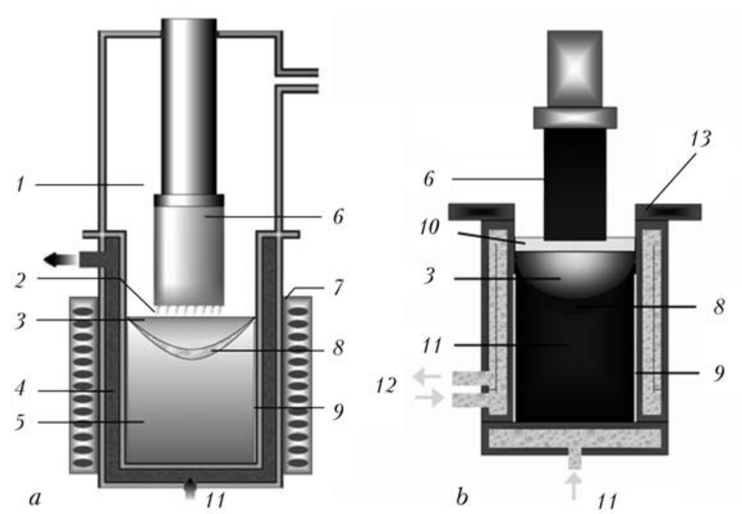

Figure 1. Schematic representation of the VAR (*a*) and ESR (*b*) process: *1* — vacuum chamber; *2* — electric arc; *3* — liquid pool; *4* — cooling circuit; *5* — solid ingot; *6* — electrode; *7* — electric coils; *8* — mushy zone; *9* — gap; *10* — slag; *11* — remelded ingot; *12* — water; *13* — cooled ingot

derstanding, since it allows to link operating parameters, such as the melting rate, ingot diameter or cooling conditions, to local solidification conditions, and thus to the ingot final quality.

The work presented here is part of a program initiated fifteen years ago in LSG2M to develop simulation software of the VAR operation, and subsequently to help optimizing the process. The first version of the numerical model SOLAR (for SOLidification during Arc Remelting) was applied to the simulation of VAR for reactive metals [2, 3]. Since then, the model has been constantly improved. In the beginning of the century, it was adapted for nickel-base superalloys and special steels [4, 5]. More recently, a similar model has been developed for the ESR process [6, 7]. The development started in 2004 with a basic hydrodynamic model of the slag, whose complexity was increased step by step. The last model has several common bases with the SOLAR code, since ESR and VAR are quite similar in terms of ingot growth and solidification.

A brief description of the mathematical models. Both models (SOLAR and SOLECS — SOLar-type ESR Complete Simulation) are based on the solution of 9 partial differential equations which represent the real physical phenomena, along with their required boundary conditions. Thus, it is possible to describe the electromagnetism, fluid flow, heat transfer and mass transfer during the growth and solidification of the ingot, and thus directly relate the melting parameters to the melt pool profile, hydrodynamic behaviour of the liquid metal, local solidification conditions and macrosegregation. At any time during the melting, the current density in the ingot is computed, as well as the electromagnetic force field, velocity field in the slag phase, liquid pool and mushy zone, intensity of flow turbulence (if any), temperature and liquid fraction maps in the whole ingot, and the composition map for any given solute. A classical RANS (Reynolds-averaged Navier-Stokes) k–ε model is included in the codes to account for turbulence. A specific development was carried out for VAR of steels and superalloys: the calculation of auxiliary ingot cooling through the injection of helium in the ingot/mould gap caused by the shrinkage of the ingot during its cooling.

Because of space limitations, it is not possible to give details of the constitutive equations. The major physical phenomena which are simulated are listed below.

Heat transfer: heat transfer within the ingot and slag by convection and conduction; heat supplied by the electric arc (VAR), Joule heating in the slag (ESR); latent heat effects related to slag and metal solidification; heat loss by contact with the mould (ingot and slag); heat loss in the lateral shrinkage gap: radiation and air (ESR) or helium (VAR) cooling.

Solute transfer: transport of solute elements within the melt pool and mushy zone; input of matter at the top of the ingot; volatilization at the free surface of the VAR ingot; solute redistribution at the solid-liquid interface.

Momentum transfer: natural convection, due to temperature and concentration gradients, and forced; convection due to interaction between the melting current and the self-induced; magnetic field, as well as electromagnetic stirring during VAR of reactive metals; laminar or turbulent flow conditions; interaction between the solid and liquid within the mushy zone.

Concerning liquid/solid interaction in the ingot mushy zone, the models use the continuum mixture theory first proposed by Bennon and Incropera [8]: the mush is assimilated to a porous solid characterized by its permeability.

The electromagnetic quantities (current density, Lorenz forces and Joule heating) are calculated at every significant change in the electric current, whereas fluid flow and heat transfer equations are solved at each time step in a coupled way. They are discretized using a finite volume method [9], with a fully implicit time scheme. Pressure-velocity coupling is treated with the SIMPLEC (semi-implicit method for pressure-linked equations-consistent) algorithm, as proposed by Van Doormaal and Raithby [10]. Due to the evolution of the mesh (related to the ingot growth), extra terms appear in the equations, as presented by Quatravaux et al. [4].

Validation of the models. The numerical simulations have been extensively validated by comparing the model results with the experimental observation of various ingots remelted in pilot plants or full-scale furnaces. This constitutes a necessary step prior to any predictive use for process optimization.

As an example, the production melting of a Ti-6-4 VAR final melt ingot was simulated, based on melting data, furnace parameters and known oxygen chemistry from the previous melt, and the predicted oxygen chemistry was compared with actual ingot results. The latter were obtained from forged product at locations corresponding to edge, mid-radius and centre, and seven vertical positions relative to the original ingot. Table shows the comparison of SOLAR predicted oxygen content versus actual analysis. The results are expressed as percentage difference between measured and predicted values.

The prediction was found to be reasonably accurate; the top of ingot centre position had the greatest discrepancy with the actual results. It is our opinion that the model can be used with confidence to predict the overall trends of oxygen segregation in optimization of melting profiles.

In the case of steels and superalloys, several industrial VAR melts were aborted by shutting off the power in order to mark the last liquid pool geometry. The macrograph obtained usually shows a sudden apparition of a very fine grain structure corresponding to a variation of the local solidification conditions. Two remeltings of 500 mm diameter maraging steel ingots have been realized, one with a low melt rate,

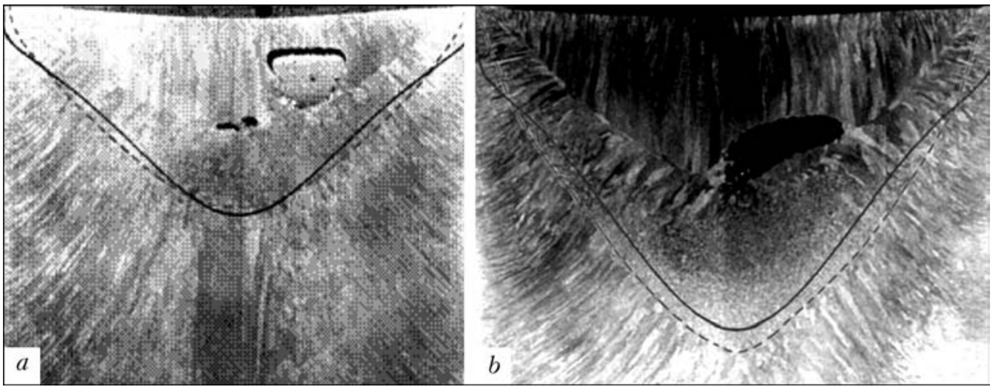

Figure 2. 500 mm diameter maraging steel VAR melts. Comparison between real and calculated pool profiles: low (*a*) and high (*b*) melt rate (experimental — dotted lines; SOLAR simulation — bold)

the second with a higher one. The experimental pool profiles, at the end of the remelting, are compared to calculated ones on Figure 2. In both cases, it is felt that such comparisons of the calculated pool profiles with the observation of macrographs demonstrate the satisfactory results obtained with the model, for a broad range of remelting conditions.

In addition, the evolution of the liquid pool during melt was evaluated by cutting a complete IN 718 industrial ingot and observing its solidification structure. During the melt, electromagnetic stirring was used occasionally to mark the pool. Figure 3 shows the experimental pool depth evolution (increase of pool depth almost until the start of hot-top — final decrease in the arc power — and visible effect of hot-top on pool depth decrease). It can be seen that the predicted and observed pool depth evolution matches very well. Such a good agreement which indicates that SOLAR is efficient for start-up, steady state and hot-top predictions.

In order to validate the SOLECS code, several electrodes were also remelted in an ESR furnace. We present here the melt of a Nimonic 80 electrode, using a classical CaF_2-based slag, with the addition of various elements such as lime and alumina. Since this melt was specifically designed to validate the model, the operating conditions were highly non-standard. Indeed, the melting sequence was composed of two stages: a first one at low melt rate and current and a second one at high melt rate and current. Nickel balls (4 kg) were added successively (at 7 moments) during the remelting. The ingot was then sectioned longitudinally and etched. As observed in Figure 4, this reveals the solidification macrostructure and the location of nickel balls which mark the different pool profiles. The experimental and calculated pool profiles are also compared on the Figure. We can observe that SOLECS results agree very well with the observation, since the evolution of the melt pool shape is fairly well predicted.

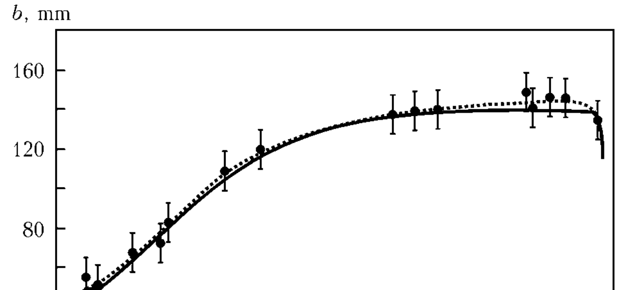

Figure 3. Full scale IN 718 VAR melt. Liquid pool evolution during melt: markers — experimental; bold — SOLAR simulation; *b* — liquid pool depth; *h* — ingot height

Ni-base nitriding. *First experiments*. The understanding of the mass transfer mechanisms and reactions between a liquid metal and a gaseous phase is important for the optimization of several metallurgical processes, including the degassing operations of steel, aluminum and nickel-based superalloys. A study of the interaction of nitrogen with liquid Ni–Cr alloys is the frame of a collaborative research between LSG2M and E.O. Paton Institute at Kyiv, which started 12 years ago [11].

A well-suited laboratory technique to investigate gas/liquid metal reactions is the levitated drop method [12], which consists to melt and levitate a metal sample in a coil supplied by a high-frequency alternating current. The use of electromagnetic levitation to study gas/liquid metal reactions offers the advantages of providing a contamination-free environment, without any crucible or substrate, and ensuring an important contact surface and an efficient stirring of the molten metal, which enable the gas–liquid system to quickly reach equilibrium.

The levitated drop method is used at Kyiv to investigate the nitriding and denitriding of various liq-

Comparison of SOLAR oxygen prediction versus actual values for Ti-6-4 final melt ingot

From top of ingot, %	Difference, %		
	Edge	Mid-radius	Centre
3.4	+1.6	+0.9	+12.1
7.6	−1.5	+0.1	+2.7
9.1	−1.5	+2.9	+1.5
25.2	−6.8	+7.5	−4.2
51.3	−4.2	+4.1	−3.0
75.5	−3.6	+0.9	−4.3
95.6	−4.5	+0.4	+0.4

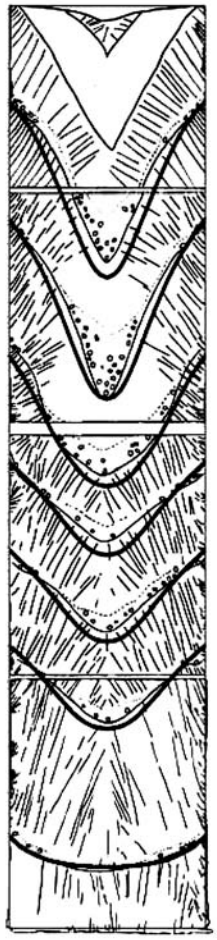

Figure 4. Full scale IN 718 ESR melt. Background: columnar grain directions and marked pools; superimposed: pool profiles calculated with SOLECS

uid metal alloys, including reactive alloys (Ti, Zr, Cr) and Ni–Cr alloys (representative of nickel-based superalloys). A levitation experiment involves exposing the levitated molten sample, maintained to a constant temperature, to a nitrogen gas flow during a controlled time interval. The gas content in the metal is obtained from chemical analysis after solidification of the sample. Such experiments give access to the equilibrium solubility of the gas in the metal at a given temperature and enable to determine kinetic data of the overall nitrogen reactive transfer at the gas/liquid metal interface.

The obtained experimental data are however insufficient to establish precisely the limiting step for the transport of nitrogen. For this reason, a numerical modelling work of the levitated drop experiment has been undertaken in parallel in LSG2M. The general objective of this model is to predict the time evolution of the nitrogen content in the metal sample during a nitriding or denitriding experiment. This requires modelling the flow of the liquid metal induced by the mixing electromagnetic forces within the droplet. Such an approach has already led to a fair description of nitrogen pick-up and removal during a Sieverts' experiment [13] in LSG2M.

In a first step aimed to determine the interfacial area, high-speed visualizations have enabled to characterize the shape of the drop free surface. The experimental facility used is schematically presented in Figure 5, *a*. The experiments are carried out in a quartz glass tube, 17.4 mm in diameter. A six-turn induction coil is installed around the tube, with two counter-turns at the top. As shown in Figure 5, *b*, the motion and shape of the levitated sample is recorded using a high-speed video camera (1000 frames/s, 768 × 768 pixels) located in front of the levitation facility. In order to quantify the geometry and dynamics of the levitated sample, an in-house computer program was developed at Nancy for post-processing the video images. This program enables to detect automatically on each digital image the drop edges and to calculate the area and the coordinates of the centre of gravity of the surface bounded by the detected edges (i.e. the apparent cross-section of the drop in the observation plane). A spectral analysis of the time evolution of the latter parameters is then performed, in order to identify characteristic frequencies of the system dynamics.

MHD modelling. The simulation of the behaviour of electromagnetically levitated droplets has been the

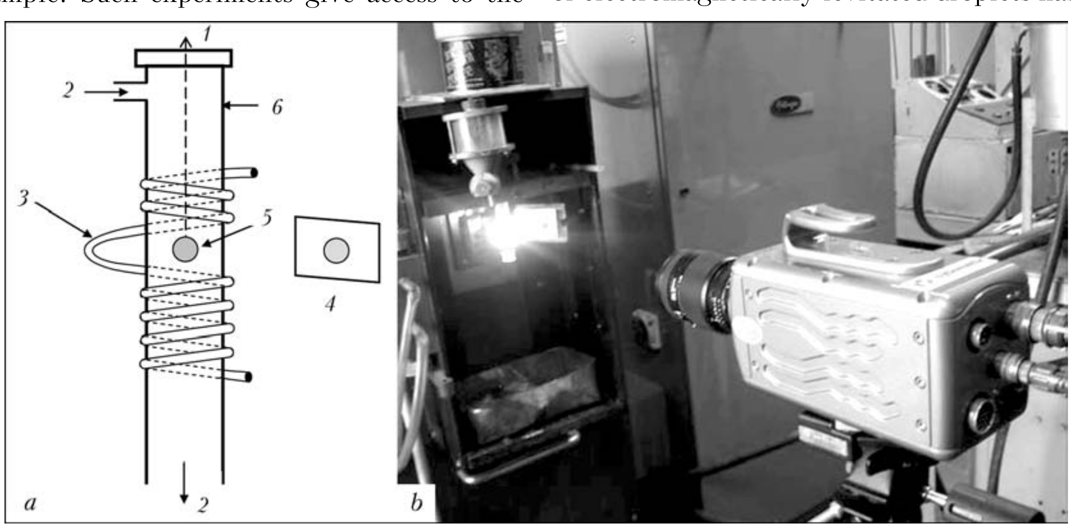

Figure 5. Levitated droplet method: *a* — principle of the experiment; *b* — experimental device to visualize the droplet behaviour; *1* — towards pyrometer; *2* — gas; *3* — reverse turn of the induction coil; *4* — miror at 45° angle; *5* — liquid drop; *6* — quartz tube

subject of numerous investigations in the literature, which have been based on a large variety of analytical and numerical techniques. A comprehensive description of the system, including the coupling between the electromagnetic field, change in the liquid metal shape and fluid flow within the drop, is a challenging task. The most prominent and complete work is the recently reported model of Bojarevics and Pericleous [14], which calculates, using a spectral solution technique, the thermal and flow fields within an axisymmetric levitated drop, simultaneously with free surface oscillations.

In a similar way, the model developed here considers an axisymmetrical liquid metal drop. The model addresses in a fully coupled way the following three aspects:

• the calculation of the distribution of the electromagnetic field produced by the coil inside and outside the drop, and distribution of Lorenz forces acting on the liquid metal;

• the determination of the turbulent liquid metal flow induced in the drop by the Lorenz forces;

• the analysis of the deformation of the free surface shape of the drop.

In particular, it accounts for the influence on the free surface shape of both the electromagnetic field and internal flow dynamics in the droplet. As a first step towards the development of a complete model, heat and mass transfer phenomena are not considered in the present work and the droplet is assumed to be isothermal. The model was built within the commercial software FLUENT version 6.2, which is a finite volume CFD package for simulating multiphase fluid flow.

Our model can be applied to simulate a levitation experiment: a Ni–20 % Cr alloy droplet, 3.1 mm in radius, is positioned under normal gravity conditions in the levitation coil at Kyiv. The equilibrium shape of the levitated drop predicted by the model is compared on Figure 6 to video images of the drop recorded during the experiment. The computed equilibrium shape was obtained by averaging the various droplet shapes calculated over the first 3 s of the simulation. The video images are the results of averaging of 400 frames. Good agreement is observed between the computed shape and both the frontal and transversal cross-sections observed experimentally. The equilibrium height of the droplet is also well predicted by the model.

In the future, the model will be extended to include both heat transfer and solute transport phenomena inside the molten droplet, so that it is suitable to simulate a complete levitated drop experiment for its application to the investigation of gas/liquid metal interactions. Ultimately, the model developed will be used, in complement to the experimentally obtained data, to establish the limiting step for the mass transfer between the gas and liquid metal, as well as the transfer kinetics.

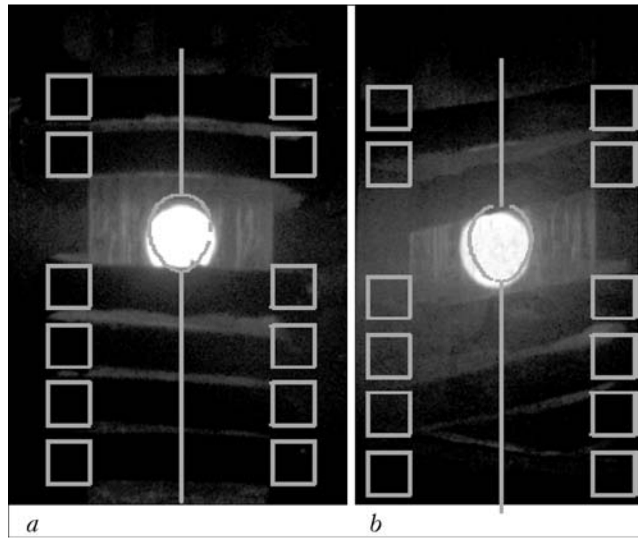

Figure 6. Comparison of the computed and experimentally observed equilibrium shape of a Ni–Cr liquid droplet levitated in the experimental facility in Kyiv: *a* — frontal view; *b* — transversal view

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MICRO-WELDING OF STAINLESS STEEL FOIL BY HIGH-SPEED LASER SCANNING

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The characteristics of micro-welding for thin stainless steel foil were investigated using high speed laser scanning with both single-mode fiber laser and pulsed Nd: YAG laser. The overlap welding of 25 μm thickness sheet could be successfully performed using a laser beam with a small focus diameter, regardless of the presence of a small gap between two sheets.

Keywords: *foil, fiber laser, Nd:YAG laser, high-speed scanning, micro-spot*

In recent years, since the size of product becomes smaller in electrical and electronics industries, then the joining of thin metal sheet has been required. Besides, the flexibility of process is important according to the accessibility in the case of small component. Fraunhofer Institute for Laser Technology (ILT) had developed the SHADOW® welding technique [1–7], in which the high speed joining with minimal distortion is possible using a pulsed Nd:YAG laser. In this technique, a continuous welding seam is achieved by a pulsed Nd:YAG laser with only single laser shot. The processing time is defined by the pulse duration of pulsed laser, and the processing length was determined by the combination of pulse duration and velocity of laser beam.

A pulsed laser would be used for the spot welding (non moved beam) or spaced spot welding (moved beam). High speed video imaging made it clear that every single laser pulse melted the material, which quickly solidified again at the end of laser pulse in the spaced spot welding [8]. The spaced spot welding repeats the heating and cooling phase, depending on the beam diameter, the seam length and overlap rate. Therefore, the spaced spot welding accompanies with high risk of distortion due to high energy input into the workpiece, since typical overlap rate of 60 to 90 % is also necessary for long processing time. The whole welding seam of simultaneous welding is only one cycle of heating and cooling phase. In the case of SHADOW® and cw-welding technique, there is also only one cycle of heating and cooling phase. Although, the whole welding seam is not melted at the same time, both techniques ensure the low energy input into the workpiece. Besides, the welded joints show a smooth surface compared to the spaced spot welding. In the contrast to simultaneous welding, higher energy intensity can be achieved, which leads to an advantage concerning the welding of high reflective material.

On the other hand, Prof. Miyamoto et al. at Osaka University had reported the possibility of high speed and high quality welding by use of a single-mode cw fiber laser [9]. However, the distortion is easy to occur by the small heat input in the case of thin foil. Accordingly, the welding with low heat input is necessary to avoid the large distortion. A smaller beam spot from the single-mode fiber laser and the thin-disk laser can increase the intensity, which leads to the low energy input into the workpiece with high speed beam scanning. It is expected that the combination of micro-beam and high speed laser scanning offers potential advantages for welding of thin metal sheet. Besides, the welding seam length can be relieved from the restrictions of pulse duration in SHADOW® technique by using the cw fiber laser and the thin-disk laser. Therefore, the characteristics of micro-welding for thin stainless steel foil were investigated by high speed laser scanning, in which the welding was carried out by a high speed scanner system with both the single-mode cw fiber laser and pulsed Nd:YAG laser for aiming at the application in industrial field.

Experimental procedures. Single-mode cw Yb-fiber laser (SPI SP-100C) of 1090 nm in wavelength and pulsed Nd:YAG laser (HAAS HL62P) of 1064 nm in wavelength were used as a laser source in this study. The laser beam of 5.45 mm in diameter from the fiber laser was expanded by 2 times beam expander. The laser beam of pulsed Nd:YAG laser was collimated to 18 mm with 100 mm focal length lens from the fiber of 200 μm in diameter. Both lasers were delivered by optical fiber, and these laser beams were focused by a telecentric type *f*θ lens of 80 mm in focal length. When the laser source was changed, optical fiber and collimation lens were replaced at the scanner head. The intensity distribution of both lasers was measured by the micro-spot monitor (PRIMES). The single-mode cw Yb-fiber laser had an excellent beam mode of TEM_{00}, and its spot diameter was 22 μm at the focusing point. On the other hand, the pulsed Nd:YAG laser had the multi-mode, and its spot diameter was 160 μm at the focusing point. The spot diameter of both lasers was almost kept constant under every laser power condition.

The waveform of pulsed Nd:YAG laser could be controlled to a rectangular shape. The single-mode fiber laser was controlled by setting the current of pumping diode laser. The fiber laser had the spike at the initial region. It was reported that the drilling for metal sheet could be carried out by the initial spike, which is 10 times higher than the set value of laser power [10]. However, its value was less than 3 times of the set laser power under this experimental condition. Therefore, it is considered that this initial spike would have little influence on the welding results compared to the former report.

The stainless steel (X5CrNi18–10) of 25 μm was used as a workpiece, which was set on the mounting device. The workpiece was fixed by the fixation plate with a hole of dimension 2 by 10 mm. The welding experiment was carried out at focusing point in the atmosphere without a shielding gas. The position of laser beam was controlled by the scanner system (SCANLAB working field 40 by 40 mm). The welding length of single-mode fiber laser was set at 6 mm, while the welding length of pulsed Nd:YAG laser was determined by the multiplication of a constant pulse duration 20 ms and velocity.

Bead on plate weld. *Welding region for thin sheet*. Since the thickness of workpiece is very thin (25 μm), the heat flux is reflecting at the backside of workpiece. Accordingly, the temperature of thin workpiece becomes higher due to a heat accumulation compared to thicker workpiece [5]. Therefore, it is required to control the laser power and the velocity of beam scanning accurately.

The welding region is investigated under several irradiation conditions by changing the laser power and the velocity of beam scanning (Figure 1). In the case of pulsed Nd:YAG laser with a large spot diameter of 160 μm, the slow velocity of beam scanning became the cutting condition under every laser power. The welding region appeared with increasing the beam scanning velocity, and its region became wider with increasing the laser power. Beyond the welding region under the high velocity condition, the workpiece could not be melted any longer. On the other hand, the single-mode fiber laser with a small focus diameter of 22 μm can melt the workpiece of 25 μm in thickness sufficiently by less than 30 W up to 2000 mm/s in the velocity of beam scanning, and its controllable region of welding is wider than the pulsed Nd:YAG laser with a larger focus diameter of 160 μm. The single-mode fiber laser can perform the welding of 25 μm in thickness under the low laser power and the high beam scanning velocity conditions. The combination of low laser power and high beam scanning velocity makes it possible to realize the low energy input per unit length, which leads to the avoidance of distortion.

Figure 2, *a* shows the scanning electron microscope (SEM) photographs of welding seam by the pulsed Nd:YAG laser with a larger focus diameter of 160 μm. Since absorptivity of stainless steel (X5CrNi18-10) is approximately 30 % at 1064 nm, the melted state could not be clearly observed at the start point. In order to avoid this problem of unstable process, the pulse shape modification is effective, in which the pulse has a high peak at the beginning [4]. However, since the diameter

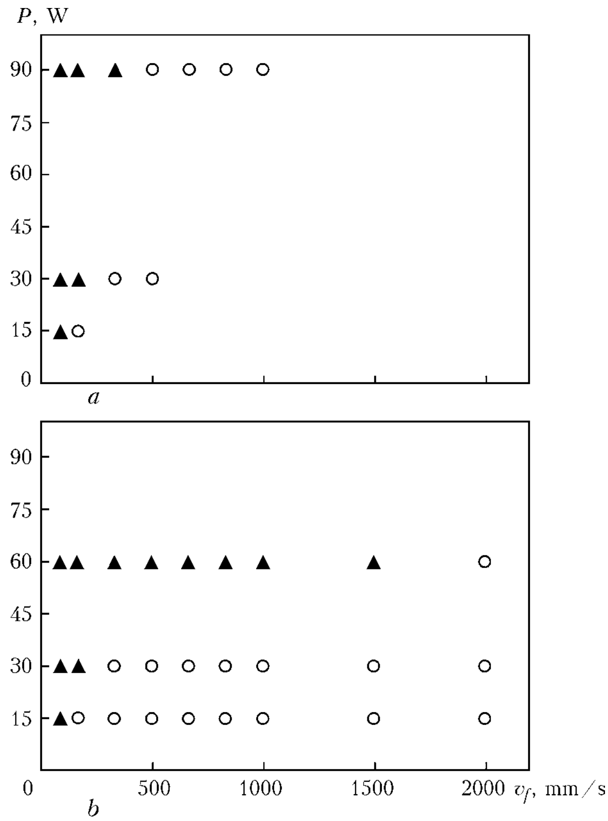

Figure 1. Map of welding (○) or cutting (▲) X5CrNi18-10 steel 25 μm thick as functions of velocity v_f of laser beam scanning and laser power P: *a* — pulsed Nd:YAG laser of 15, 30 and 90 W, power density of $7.4\cdot10^4$, $1.5\cdot10^5$ and $4.5\cdot10^5$ W/cm^2 respectively at focus diameter d_0 = 160 μm; *b* — single-mode fiber laser of 15, 30 and 60 W, power density of $3.9\cdot10^6$, $7.9\cdot10^6$ and $1.6\cdot10^7$ W/cm^2 respectively at d_0 = 22 μm

of laser beam is larger than 6 times of workpiece thickness, the same method with a high peak at the beginning of pulse accompanies the risk to make a hole at the start point. The unavoidable acceleration time of beam scanning makes it difficult to control the input energy into the workpiece at the start of process.

On the other hand, the single-mode fiber laser, used without pulse control, produces a good result from the start of the weld (Figure 2, *b*). The laser beam was effectively absorbed from the start of beam scan, while at the end point a cavity can be observed, which was generated on closing of keyhole as the beam was switched off. At the start point of Figure 2, *b*, the widening of top bead width was observed. This phenomenon was observed only under low velocity condition. Therefore, it is considered that due to a higher energy input to the surface region of the weld bead, the keyhole extruded the molten material to backward side of laser beam.

Figure 3 shows the approximated results of the temperature distribution at the cross section of laser beam scanning line with the steady thermal calculation program «Laser Weld 3D», which was developed by Fraunhofer Institute for Laser Technology. The surface temperature of workpiece was less than the evaporation point under the condition P = 30 W, v_f = 333 mm/s, d_0 = 160 μm, that is the heat conduction welding condition. Therefore, the cavity was not ob-

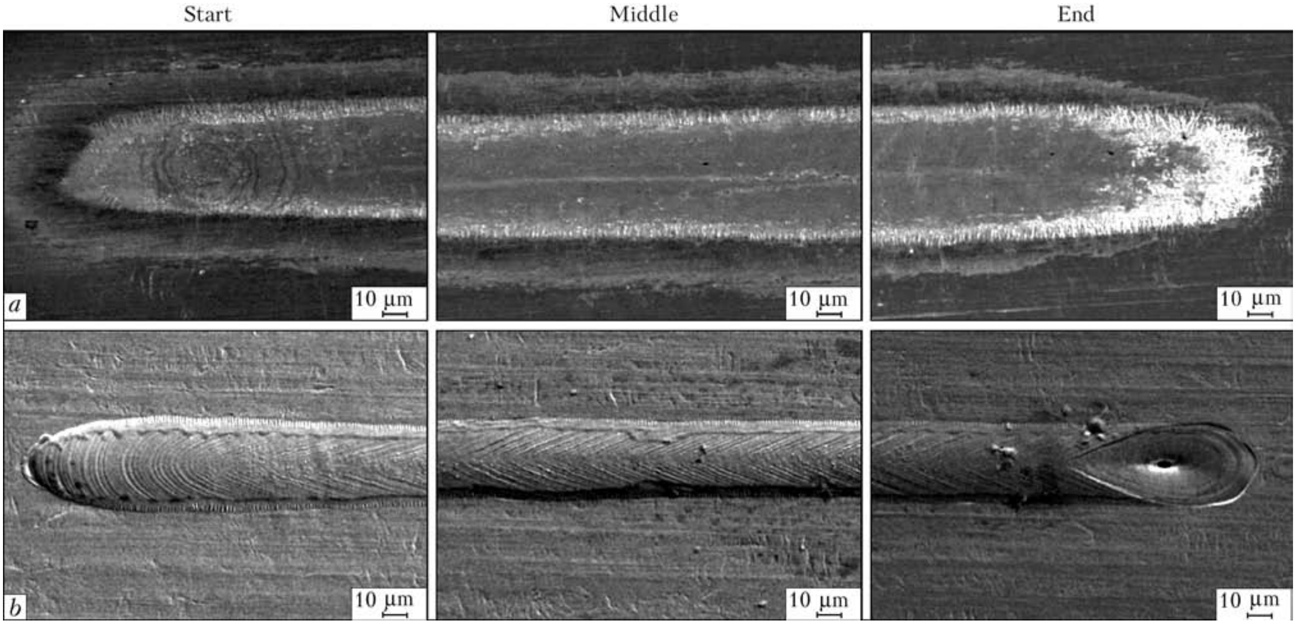

Figure 2. SEM photographs of weld performed by pulsed Nd:YAG laser (P = 30 W, v_f = 333 mm/s, d_0 = 160 μm) (*a*) and by single-mode fiber laser (P = 15 W, v_f = 666 mm/s, d_0 = 22 μm) (*b*)

served at the end point (see Figure 2, *a*). The boundary between the welding seam and the base material was not clear. On the other hand, the single-mode fiber laser with a small focus diameter can increase the surface temperature above the evaporation point under the condition P = 15 W, v_f = 666 mm/s, d_0 =22 μm (see Figure 2, *b*). Also, a part of melted material is moved toward the surface direction, and the welding seam can be clearly observed with sharp boundary line. From these results, the welding with single-mode fiber laser was mainly investigated in the next step, because the small focus diameter is effective to control the welding condition for thin sheet foil.

Bead width and penetration depth by single-mode fiber laser. Figure 4 shows the bead width and the penetration depth with the energy density by single-mode fiber laser. The energy density was calculated using equation (1):

$$E = P/v_f d_0, \qquad (1)$$

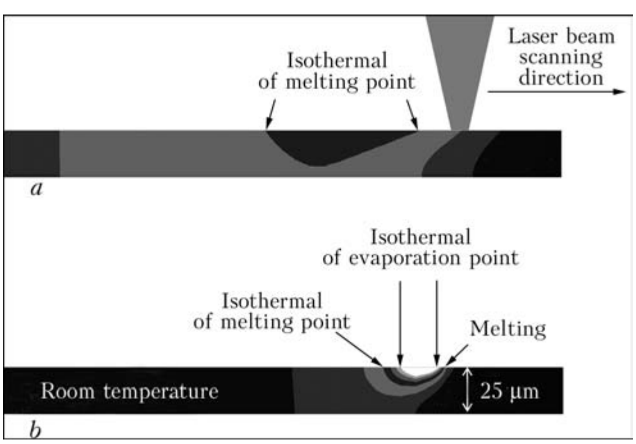

Figure 3. Approximation of temperature in 25 μm thickness sheet by steady thermal calculation at absorptivity of 30 %: *a* — P = 30 W; v_f = 333 mm/s, d_0 = 160 μm; *b* — P = 15 W, v_f = 666 mm/s, d_0 = 22 μm

where E is the energy density; P is the laser power; v_f is the beam scanning velocity; d_0 is the beam diameter at focus point.

As shown in Figure 4, *a*, the bead width increased in proportion to with the energy density less than 1 J/mm^2, however, the increasing rate of bead width became lower for the energy density higher than 1 J/mm^2. The full penetration was accomplished for

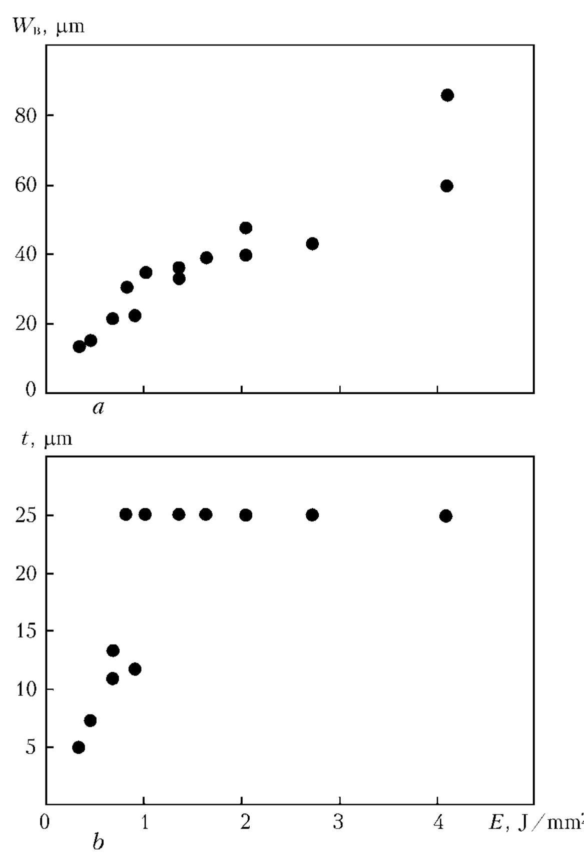

Figure 4. Bead width W_b (*a*) and penetration depth t, μm of weld bead performed by single-mode fiber laser on X5CrNi18-10 steel 25 μm thick at d_0 = 22 μm

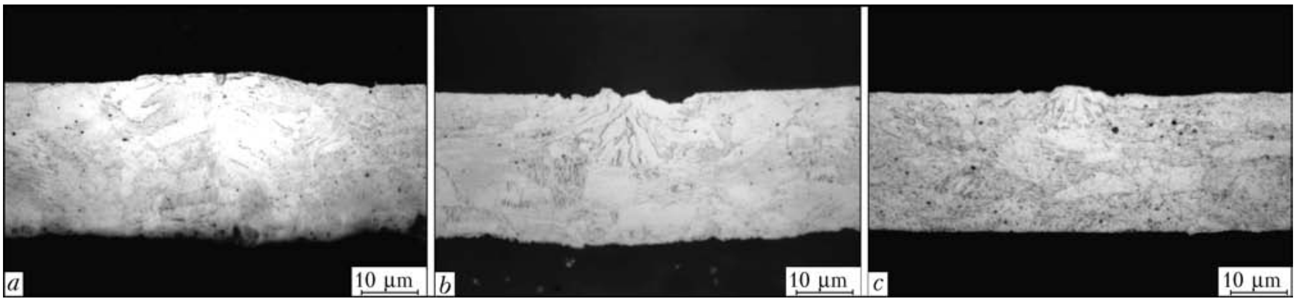

Figure 5. Cross section of weld bead performed by single-mode fiber laser at P = 15 W, v_f = 666 (*a*), 1000 (*b*) and 2000 (*c*) m/s

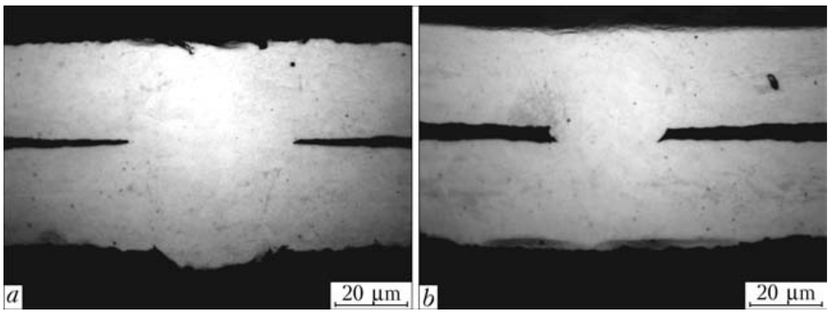

Figure 6. Cross section of two thin sheets welded by single-mode fiber laser: v_f = 166 (*a*), 1000 and 2000 (*b*) mm/s at P = 15 W

the energy density higher than 1 J/mm^2, while the quasi penetration welding can be performed for the energy density less than 1 J/mm^2. Also, the penetration depth can be controlled by the energy density with a small focus diameter (Figure 4, *b*). At the energy density 1 J/mm^2, the penetration depth increases drastically from 13 μm in penetration depth to 25 μm of full penetration depth.

Figure 5 shows the cross section of 25 μm stainless steel foil welded by the single-mode fiber laser at laser power 15 W. The fine weld bead was obtained without any humping. These shapes of weld bead at high velocity indicate that these welding were carried out by the heat conduction. However, approximated surface temperature was higher than the evaporation temperature under every condition of single-mode fiber laser with 3.9·10^6 W/cm^2, which is around the boundary region between the heat conduction and the deep penetration welding with the keyhole [2]. The keyhole might be generated, since the surface temperature would be more than evaporation point. However, the beam scanning velocity was extremely fast, and the depth of keyhole could not become sufficient large size. Then, it is considered that the bead shape is similar to the heat conduction welding. It would be discussed whether this weld bead can be done by heat conduction or by keyhole welding in the further study.

Overlap welding. The overlap welding of two stainless steel foils 25 μm thick was carried out by the single-mode fiber laser. As shown in Figure 6, the fine bead was also obtained without any humping, undercut and drop out. Although the small gap remained between two foils, the overlap welding could be successfully performed (Figure 6, *b*). In the case of thin foil, even if two foils could be mounted without gap, a little distortion was unavoidable from the start of laser irradiation. Because the thin foil has very low rigidity, and the large temperature gradient (see Figure 3, *b*) generates the high thermal stress, which can deform the thin foil sufficiently. This phenomenon has a great influence on a line welding compared to a spot welding. If the welding can be performed regardless of small gap distance between two foils, it is greatly effective technique for thin foil welding. Moreover, low energy input into the material is also effective to avoid a large distortion. Therefore, it is considered that the combination of micro-beam and high speed laser scanning has potential advantages for thin metal foil welding.

Control of welding seam. Figure 7 shows SEM photographs of welding seam by various waveforms of laser pulse, which was measured by a high-speed photo detector. Single-mode fiber laser was irradiated at scanning velocity 1000 mm/s, and the laser peak power was kept 30 W. Three types of pulse waveform were used. The first type is a rectangular pulse of peak power 30 W, and this is the same as the previous experiment. The bead width was kept constant, and the shallow cavity was observed at the end point of

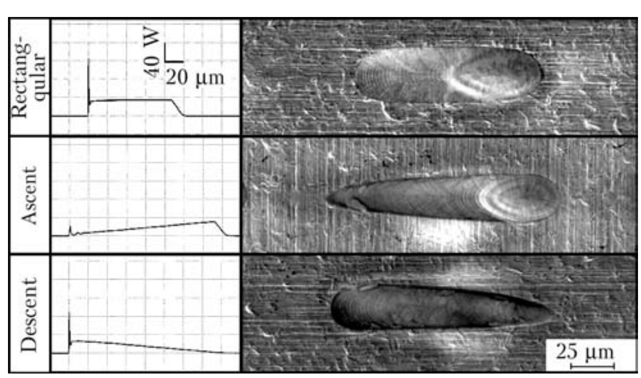

Figure 7. SEM photographs of weld at controlling the current of pumping diode laser in single-mode fiber laser (v_f = 1000 mm/s)

laser irradiation due to the movement of melted material. The second type is a ascent pulse up to 30 W, and its bead width increased gradually according to the change of laser power even in the short length. Also, a shallow cavity was observed at the end point as shown in a rectangular pulse. The third type is a descent pulse from 30 W, and its bead width decreased gradually according to the change of laser power. In the case of falling pulse, the cavity could not observed at the end point, since the laser power decreased by controlling current of pumping diode laser. This technique is effective to avoid the cavity at the end point of laser irradiation. The welding seam was well controlled by the combination of high speed scanning and laser power control with a single-mode fiber laser even in the case of 25 μm thickness sheet foil.

CONCLUSIONS

The characteristics of micro-welding for thin stainless sheet were investigated by high speed laser scanning with both single-mode fiber laser and pulsed Nd:YAG laser. Main conclusions obtained in this study are as follows:

1. The results showed a narrow welding region obtained using a laser beam with a large focus diameter of 160 μm without pulse control, while a small focus diameter of 22 μm was found in general to provide a good control of the welding state.

2. A small focus diameter could result in an excellent welding seam from the start, even without pulse control.

3. The penetration depth could be controlled by the energy density with a small focus diameter of 22 μm for the energy density less than 1 J/mm^2.

4. The overlap welding of 25 μm thickness could be successfully performed, regardless of the presence of a small gap distance between two foils by high speed scanning of laser beam with a small focus diameter of 22 μm.

5. The welding seam could be controlled accurately by the combination of high speed scanning of small focus diameter and pulse waveform control of laser shot even in the case of 25 μm thickness.

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WELDING TELEROBOTIC SYSTEM APPLYING LASER VISION SENSING AND GRAPHICS SIMULATION

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In this paper a design and implementation of welding telerobotic system (HIT-WTRS) is presented, which is dedicated to remote welding maintenance in inaccessible or hazardous environment. The system integrated three technologies, namely laser scan vision sensing (LSVS), stereoscopic video display, and virtual environment-based plan and control. Three control modes are emphasized in this system respectively, which are teleteaching, autonomous control and virtual environment-based supervisory control. The laser scan vision sensor is used as autonomous welding path planner, and is also employed to provide the welding joint profile feature point for teleteaching. The graphics environment is used as simulation and path plan platform, and is also used as multi-viewpoint supervisory window to monitor the remote environment when arcing. Some performance results and ways to improve the system are discussed.

Keywords: *laser vision sensing, graphics simulation, telerobotic system, remote welding*

Welding technology has long term been desired to use in some extreme environments where it is inaccessible and hazardous such as radiation site, underwater and space. However, remote welding tasks cannot be performed by totally autonomous robot for the restriction of artificial intelligence, sensing technology and computer decision-making. Teleoperation is gaining a lot of attraction in remote welding fields that human operator (HO) can interactive with robotic system applying appropriate control strategies and sensing technology [1].

The earliest remote welding was mainly used to repair nuclear components. Welding maintenance project of Canada Douglus Point nuclear power reactor leak accident indicated that remote welding could be implemented in practical project [2]. In the project, 2 manipulators and 7 cameras are employed as welding execution mechanism and monitor facility respectively. Agapakis and Masubuchi [3] in MIT consider that welding teleoperation should not simply imitate manual welding. Vision sensing and computer assistance programming is important for remote welding.

Several teleoperation systems are established for remote weld inspection and repair. In French Nuclear Energy Program, Framatome has developed a telerobotics system for the welding repair and inspection [4]. RoboCAD software is used for welding path plan and environment simulation. Broome etc. [5] developed telerobotic control system for subsea welding seam inspection as part of the ARM project. 3D video display and viewpoint transition technology are employed. Multi control modes such as direct manual mode, enhanced manual mode, semi-automatic and automatic mode are used to control the manipulator to determine the trajectory of welding and grinding.

Our lab started the research in 1994. Zhang [6] established the arc welding master-slave manipulator teleoperation experiment system. He concluded that weld tracing velocity faster, the worse weld quality, and 3D video display can help to enhance the weld trajectory tracing accuracy. Lu [7] applied shared control and distributed control into arc welding telerobotic system for welding torch motion control.

There are three characters of remote welding as follows [8]:

- the welding process is complexity, which has many control parameters such as torch position and pose (POSE), arc length, velocity and so on;
- it is required higher weld tracing precision and lower velocity error in the process. As a result, task space and welding environment need to be recognized accurately;
- force sensor cannot be used because the welding torch does not touch with environment in welding and arc force is too weak. The vision sensing is the only way to feedback the information of remote site.

Therefore, welding operation is difference from parts assembly, for which appropriate vision sensing, input device and control strategies must be used in remote welding system.

In remote welding, HO is the decision-making center, and welding robot in remote site is execution center. It is most important to combine the high intelligence of HO and the performance capability of welding robot to enhance the flexibility and efficiency of telerobotic system. The control philosopher should be global supervisory control and local autonomous control.

Laser scan vision sensing (LSVS) technology can extract weld feature point information, and send it into robot controller to adjust the POSE of welding torch [9]. Because laser is active light source, it is not suffer from the restriction of environment background light. If reducing the sensor dimension, it is more suitable to perform welding task in flexibility environment. Graphics environment-based plan and control is also the most important method in teleoperation technology that can be used for welding path plan and real environment simulation. When arcing, video display is inactivated, and the working scene can be monitor only by virtual environment.

In this paper, the design and implementation of a welding teleoperaiton system–HIT-WTRS — based on LSVS and graphics simulation is presented. Firstly, the physical and software architecture are all presented to illustrate the system details. Moreover, the advanced tools such as LSVS, 3D video display and graphics environment-based plan and control are all applied in the system, which can be used to perform direct manual control, teleteahcing, supervisory and autonomous control. Finally, the experiments are performed to illustrate the performance of the welding telerobotic system, and the results are discussed.

System architecture description. The system architecture has been designed to integrate operator's global decision-making intelligence and the robot's local performance capability as possible, and to give operator the maximum degree of teleoperation. The main goal is to enhance the welding tasks performance capability in unstructured environment and make the operator perform remote welding tasks in an easy and comfortable way.

Hardware architecture. The hardware architecture of the experimental system is based on two parts: operator's local side and remote working side (Figure 1). Communication between them takes place through LAN based on TCP/IP protocol to guarantee the operation efficiency and electrical isolation. The manipulator controller works as sever to provide data and outer computers work as client such as the LSVS, supervisory computer, and graphics workstation. All of them connect to a HUB.

The operator's local side includes the following components: space mouse, supervisory control computer, graphics simulation workstation, stereoscopic display and other auxiliary devices. The function of supervisory computer has three aspects:

• show running information of the system, tasks performing status, and video display of remote site;

• send operator's control commands to real environment and virtual environment;

• process the information flows, and perform control mode plan.

WMHMI runs on Win2000 operation system, and developed by Visual C^{++} 6.0. IGRIP software running on Unix system is used as welding path plan and graphics simulation platform. Stereoscopic display based on page-flipping display mode is developed by us.

Remote working side take charge for welding tasks performing, which is composed of as following devices: slave 6 DOF welding manipulator, panoramic DSP200X zoom digital camera, two stereoscopic cameras, two cradle heads, welding power, laser vision sensor, welding torch and other auxiliary devices.

The HIT-WTRS consists of inner, middle, and outer control loops. The inner control loop is composed of high-bandwidth joint controllers. The laser vision sensor and robot controller are in a close control loop at remote site that compose of the middle control loop. The supervisory computer, robot controller, HO, video display, and space mouse compose of the outer

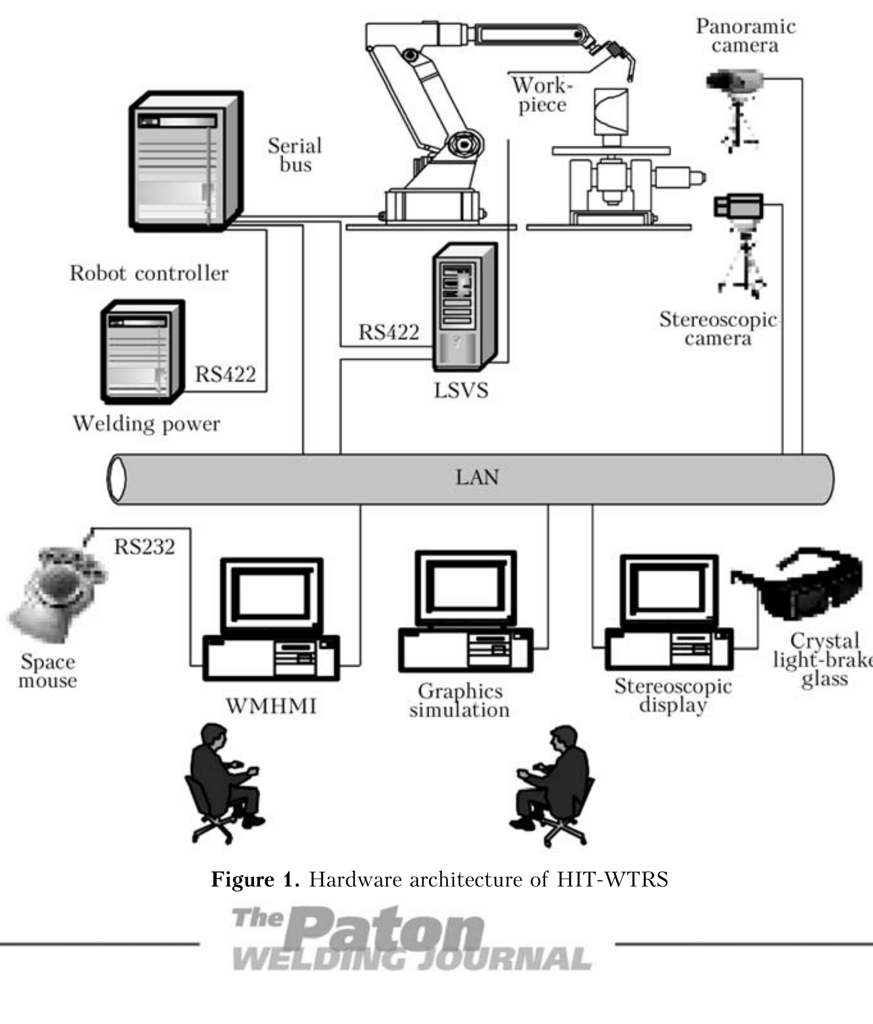

Figure 1. Hardware architecture of HIT-WTRS

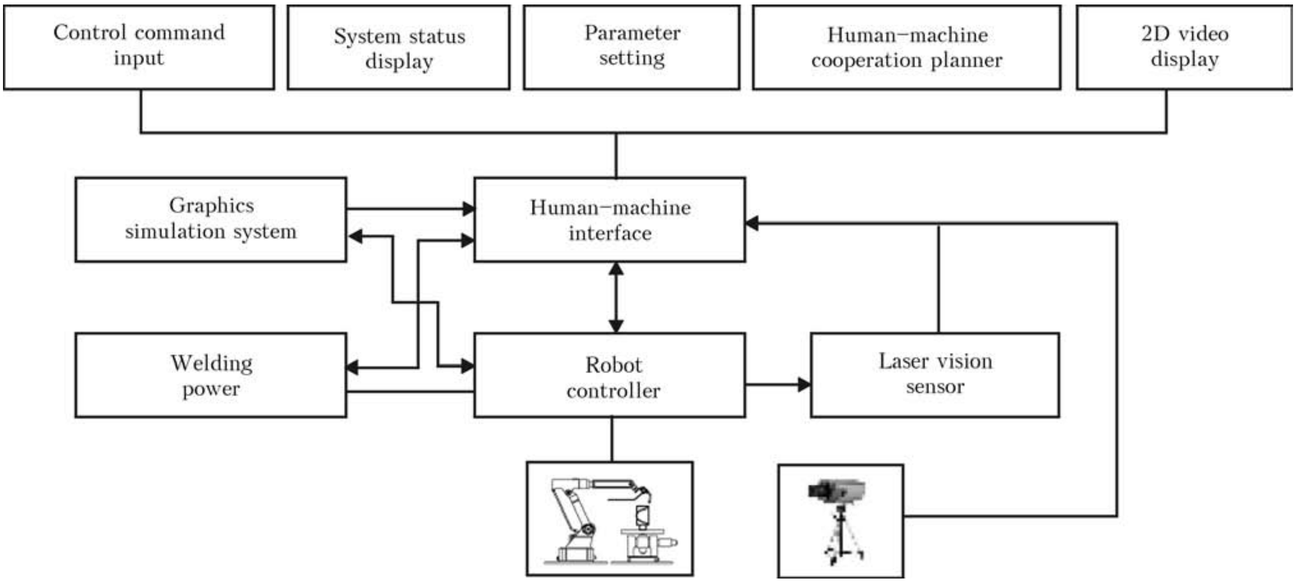

Figure 2. HIT-WTRS software architecture

control loop. HO's control commands project into autonomous plan level, motion level and intelligence level by real-time control, tasks planning, and system decision.

Software architecture. The software architecture also can be divided into operator's local side and remote side (Figure 2). Human machine cooperation execution modes range from full manual control to full autonomous control passing through shared control, interactive control, and supervised autonomy control mode.

In local side, the WMHMI and graphics simulation work as client. The WMHMI is main interface of welding telerobotic system that can be employed as the only interface to operate welding robot and torch, and also can be assisted by virtual environment interface. The WMHMI consists of six modules: control command input, 2D real scene display, system status display, human–machine cooperative planner, parameters setting, and communication module. The robot controller sends back robot running trajectory data, and display in the WMHMI by grid curve and message dialog. The real working scene image, which is send by panoramic camera, is displayed in the WMHMI, and the virtual work is displayed in graphics simulation system. The human–machine interface is shown in Figure 3. IGRIP software used as welding path plan programming and virtual graphics display. When the welding arcing, the system is used as supervisory control window replace panoramic image display. The velocity or position of control input device such as joystick and space mouse are used to generate low level commands and transmit this continuous commands or discrete commands to virtual environment and physical environment. Laser vision has the ability of weld sensing and tracing. As the weld is regular, it is used as path planer to scan and trace weld, and as welding is irregular, it extracts feature point of welded joint profile for teleteaching control mode.

In remote site, the robot controller worked as sever. After the client connected, the controller sends the information to client site. The LSVS scan the feature point of weld, and send it to controller. Based on this vision information, the operator can analyses the state of the manipulator in the remote environment and supervise performing process. In the virtual environment, the torch motion path can be planned and the low level commands as a file download to remote welding robot controller.

Stereoscopic vision based manual control. *Stereoscopic vision display*. The stereoscopic vision shows images from the stereoscopic cameras placed at slave manipulator site that is formed the by two image overlapped in computer which are transmitted by two difference cameras in remote site. The operator must wear special crystal shutter glasses to see the stereoscopic images. The character of stereoscopic vision display is to show the operator the sufficient depth perception, which enhances comprehension of unstructured environment. In welding telerobotic system, the depth perception is important especially, which can help operator lead welding torch in a little range.

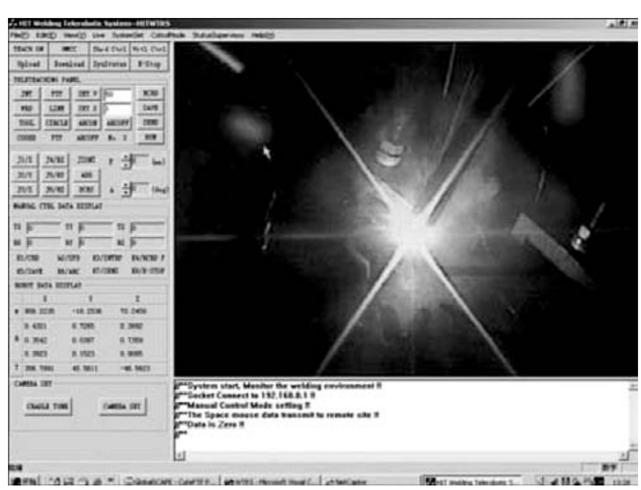

Figure 3. WMHMI functional architecture

Figure 4. Stereoscopic cameras with cradle head (*a*), and operation site working with direct manual control assisted by stereoscopic display (*b*)

HO's eyes have the ability of image automatic matching and identifying under the control of optic nerve. As similar to this, the cross angle of the two cameras defined the stereoscopic vision display zone. In order to ensure the right image and left image arriving in a same time, the CCD camera must be synchronized trigger outside. Generally, one video signal is the outside synchronize signal to trigger the other video. The images are shown alternatively to each eye and are synchronized with the crystal light shutter glasses. It shows 70 images per second, 35 alternative images for each eye. This frame rate and the high quality of the stereoscopic images provide the operator with an excellent way to obtain sufficient depth perception.

Figure 4, *a* are the two stereo cameras with controllable cradle head, which work in the remote site. In the system, left camera signal is used to trigger the right camera. The implementation procedure is as following: left eye camera gathers the video signal to send into video distributor. On the output side, one channel video signal inputs into image collection card directly, and the other channel signal works as trigger signal to trigger right eye camera. Accordingly, the method ensures the synchronized of left image and right image. Page-flipping display modes are used to time-sharing display that make the image have high resolution and refresh rate. The software programming is based on VC^{++} programming language. Figure 4, *b* is the local work site use stereoscopic vision display to operate welding torch remotely.

Direct manual control. The space mouse output increment data that can be express as $\dot{X}_{HC}(\dot{x}, \dot{y}, \dot{z}, \dot{a}, \dot{b}, \dot{c})$. The previous three data are poison increments and the latter three are pose increments. The fundamental principle of the manual control is to transform $\dot{X}_{HC}$ to velocity control variable of joint coordination θ. The control architecture is shown in Figure 5. The time-varying manipulator Jacobian matrix maps joint rates to Cartesian rates of the T_6 frame: $X_{t6} = J\theta$. The equation must be inverted at each control step. First, the X_{t6} must be inverted into X_B, and by the equation $X_B = J\theta$, to joint control, that can be perform by PID control algorithm. Next, according to forward kinemics, the θ can be inverted to X'_{t6}, $X_{t6} = X'_{t6} + \dot{X}_{t6}$.

LSVS-based teleteaching and autonomous control. The LSVS technology extracts joint features point, and feedback the data to manipulator's controller continuously. According to the deviation of feature point and welding torch practical position, welding process can be performed autonomously. At the case of weld is discontinuous, the feature point can be used as teaching point, which is the concept of teleteaching assisted laser vision sensing.

Laser vision sensing technology. Figure 6, *a* is the laser scan tracing sensor developed by our lab. The principle is shown in Figure 6, *b*, it consist of laser diode, photoelectricity signal received system, signal pre-disposal board, scan driver motor and angle signal

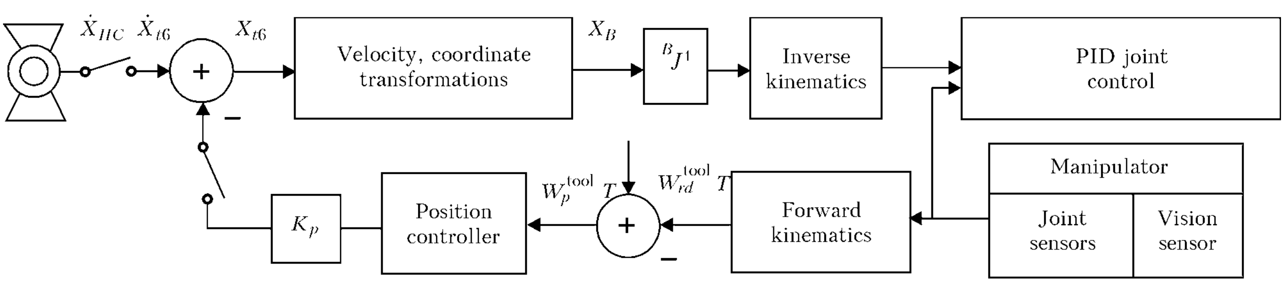

Figure 5. Control architecture of direct manual control

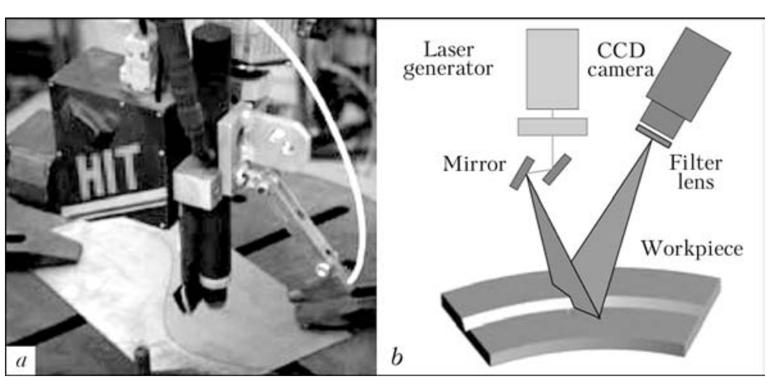

Figure 6. Physical architecture of LSVS (*a*) and sensing principle (*b*)

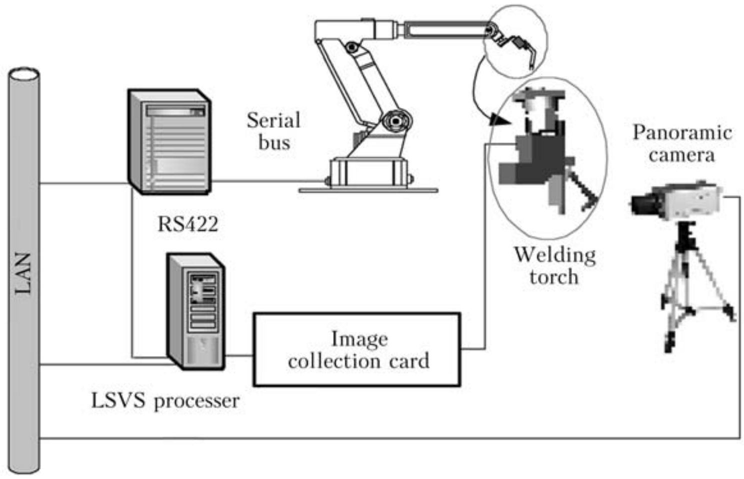

Figure 7. Autonomous control architecture

disposal board, photoelectricity coder and industry computer. The scan driver motor rotates the mirror to reflect the laser to workpiece surface, and then the laser is reflected to CCD camera. The range data from start point to the surface of workpiece and the range data from the images captured by CCD camera to center point have simply linearity relationship. Weld profile geometry data in sensor coordination can be acquired by disposing the pixel on CCD camera.

Autonomous control. The laser vision sensor has the capability to tracing weld autonomously. In HIT-WTRS, the laser vision system is used as local autonomous system. In working process, vision sensor is mounted on welding torch. Suppose that the transformation matrix between sensor and torch is ^tT_s. In sensor coordination, feature point of welded joint is T_w, then the POSE of weld feature point in base coordination could be expressed as $^bT_w = {}^bT_6{}^6T_t{}^tT_sT_w$, and saved in circulate queue. When the torch POSE in the next machine circle is compared with the torch POSE in the current machine circle, we get the drive vector D_t:$D_t = [\Delta x, \Delta y, \Delta z, \Delta\partial, \partial y, \partial z]^T$, that is used to control torch POSE.

Figure 7 shows the autonomous control architecture. The feature point data are added to the position of manipulator in controller, which is composed of the inner loop. The autonomous control is appropriate to trace continuous weld and no obstacle in the working space.

Teleteaching assist by LSVS. In general industry applications, the LSVS is used as autonomous path planer at the case of weld is continuous. When the weld is discontinuous, the autonomous control is invalidation. The joint feature points can be used for teleteaching.

When the supervisory computer works in teleteaching mode, panoramic vision and stereoscopic vision display are used to show the information on remote site, moving the manipulator 10–40 mm above weld (didn't adjust welding torch accurately). At this time, laser vision system processes the joint profile image, and calculates the joint feature point data in real-time. These data are transmit to manipulator' controller by RS422 serial communication.

After completed the teach mode setting, such as welding speed, interpolate mode and arc status by space mouse button, press record button to send the acquisition joint data signal to controller. Then the current manipulator' POSE are transmitted to supervisory computer and record in teach01.ttr file. After accomplished the teaching process, a whole welding path are download to manipulator controller. The controller commands format are as follows:

```
STARTP                          //*start program
MOVJ VJ = 20.000                //*joint motion, velocity:20
...
ARCON                           //*arc on
MOVL VL = 20.000                //*welding speed
...
ARCOFF                          //*arc end
MOVL VL = 20.000                //*line interpolated, v = 20.0
...
ENDP                            //*stop program
STARTD                          //*joint value record start
-11.25/33.84/-43.80/-48.81/35.64/155.97/
...
ENDD                            //*data end
```

The special algorithm architecture is shown in Figure 8. Teleteaching can be divide three phases: setting weld type; scan joint profile and process feature point; welding robot record and running.

Graphics environment-based supervisory control. *Graphics simulation system*. Graphics environment based control technology can be divided into two facts: we can use space mouse to operate the robot in virtual environment tracing weld that can train HO to understand welding teleoperation procedure and the system performance character, and we can use the

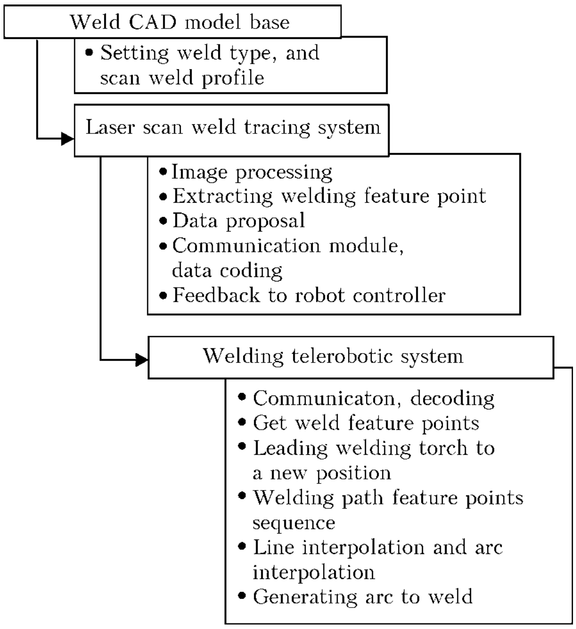

Figure 8. Algorithm flow of teleteaching assist by LSVS

graphics simulation environment as the monitor when welding arc light disturbs the vision display.

IGRIP is used as the simulation software platform. Virtual environment calibration technology (VECT) is used to calibrate the POSE relationship by human–machine interactive matching the feature point. The POSE of torch and weld is transmitted from the remote work site to the system, and virtual robot is calibrated POSE according to camera viewpoint. After completing calibration of the real robot and environment and virtual robot and environment, the IGRIP can perform tracking path plan, programming translation, collision check and so on. The calibration and tasks plan flow chart is shown in Figure 9, *a*. During remote welding proceeding, arc light makes vision feedback disabled. At this time, we can observe manipulator and torch POSE change and the welding proceeding through the graphics simulation environment. Graphics environment-based control established the bridge between physical manipulator and task environment with the virtual manipulator and environment in the IGRIP.

Calibration of real environment and virtual environment. VECT based on human–machine interaction is developed from the viewpoint of application. It extracts the image feature points by a human–machine interaction mode which make use of HO's capabilities of recognition and decision making to solve the problem of corresponding feature points matching. As shown in Figure 10, we can calculate to get the relationship matrix of real environment (RE) and virtual environment (VE) M_w^i by VECT. The vision system contains two auto-zoom cameras and a cradle head structure, while the focal length and cradle head parameters can be adjusted in real-time.

We can obtain a high localization precision by the vision system, which is very flexible and adaptable. Camera calibration is done by a nonlinear least-squares algorithm combined with a linear one on line, and the whole body localization of a structured part is achieved by a whole body localization algorithm while the fea-

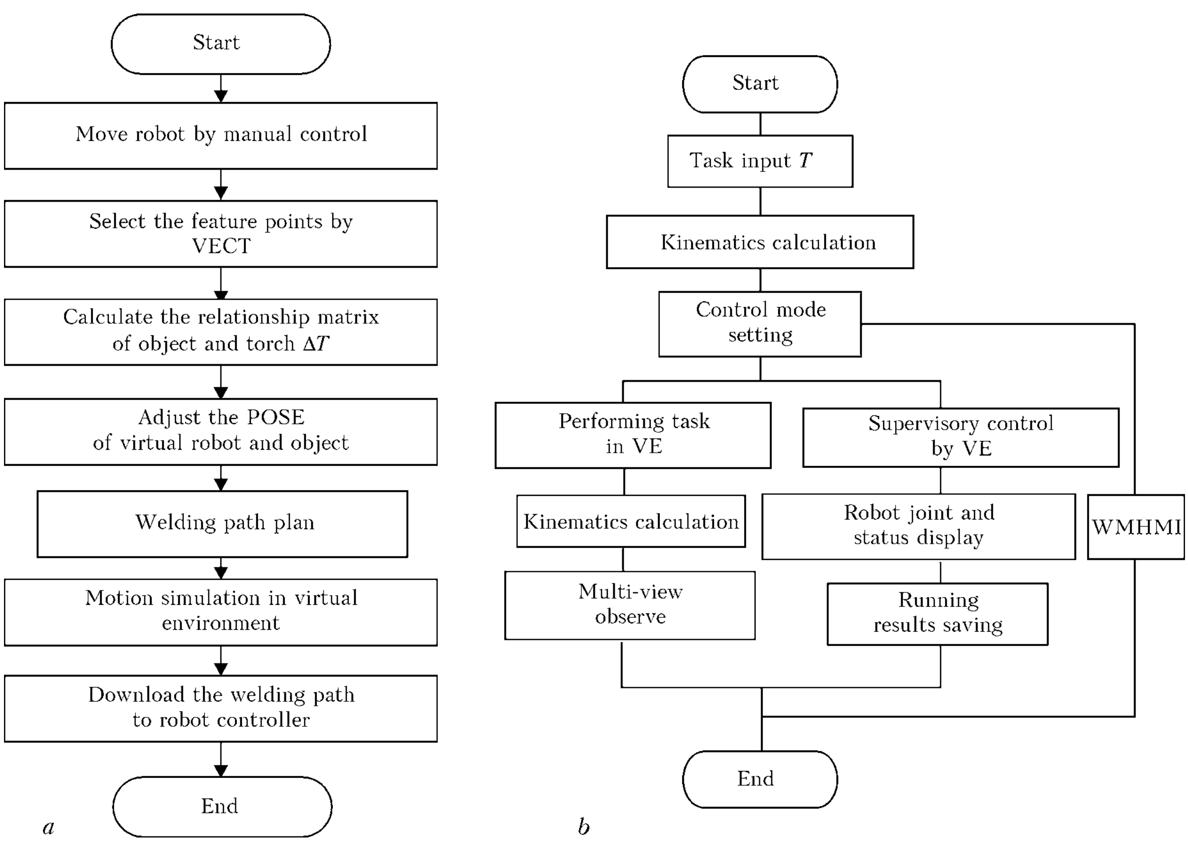

Figure 9. VECT and welding tasks plan flow chart (*a*), and graphics-based supervisory control flow chart (*b*)

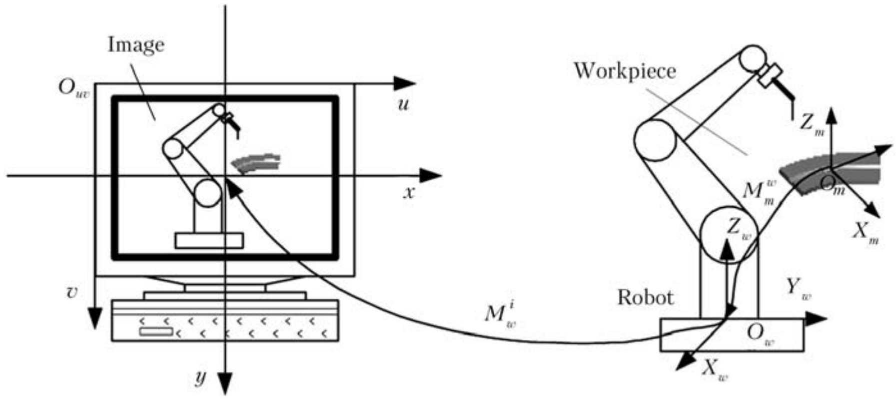

Figure 10. Mapping from real environment to virtual environment

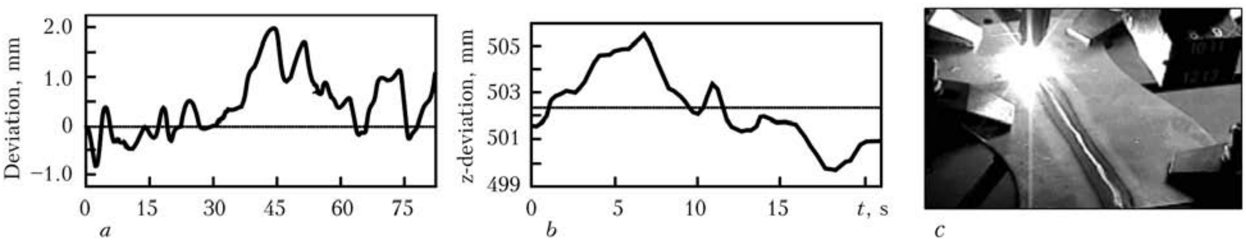

Figure 11. Teleoperation process of straight-line welding: *a* — cross deviation; *b* — in *z*-direction; *c* — welding process

ture points localization is achieved by a point localization algorithm. For calibrating the VE of different part types, a VE calibration module is developed in IGRIP based on VECT, three points calibration of auxiliary feature points and four points calibration of circular reference part.

Execution tasks by HIT-WTRS. The welding telerobotic system is developed for hazardous and unreachable environment that these tasks performing must be in specific procedures. These procedures aim at increasing system efficiency and reducing the task performing time. Another important factor to be considered is to reduce the effort exerted by the operator who works in the control loop. The tasks in unstructured environment can be performing in several control modes. They are based on range from traditional manual control to supervisory control. As a result, the two experiments are designed to test the system performing character. The welding method employed TIG, which welding process has the character of stability little welding spatter. The experiment tasks presented as straight-line weld and space helical-line weld.

The space mouse is used as hand controller, stereoscopic display, 6DOF arc welding robot, TIG welding torch and digital zoom video. Straight line long is 25 mm, weld width is 1 mm in V-type joint. Welding torch pose is kept constant. The HO hand controls the three DOF of welding rate, welding torch height and cross direction, striking the arc by high-frequency and manual welding along the straight-line weld. In Figure 11, *a* is the cross deviation curve of straight-line weld by manual control, and the average deviation is 1.5 mm. Figure 11, *b* is deviation curve of welding torch height. The maximum deviation from average position is 3.2 mm. Figure 11, *c* is the welding process scene.

Another experiment on space helical-line welding based on teleteaching mode and graphics environment-based supervisory control is presented as followed. The object is helical-line weld on pipe with diameter of 250 mm and height of 200 mm. 20 teach points are

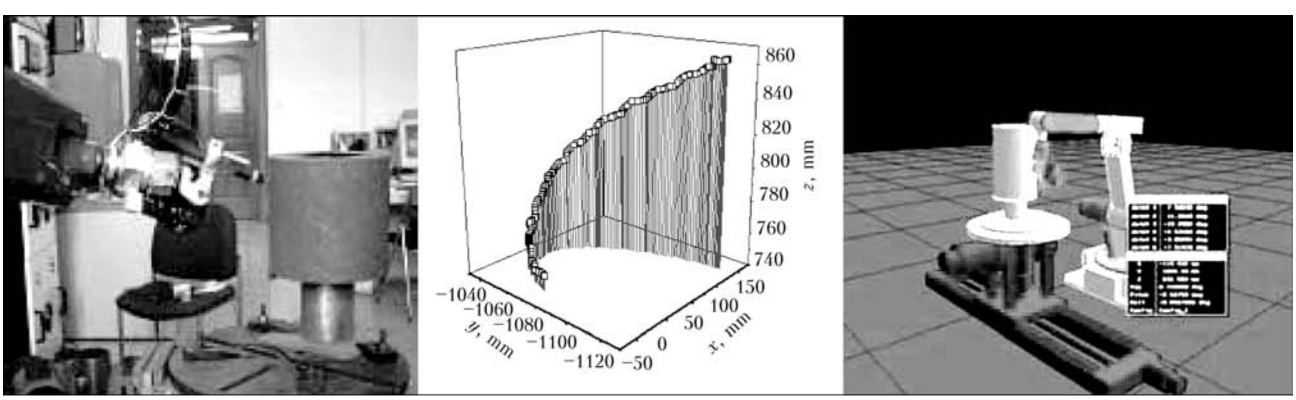

Figure 12. Teleteaching helical-line welding assisted by LSVS

record on the weld and input into a file. Then, download to remote robot controller, and play back the welding path. The welding process is supervisory in graphics environment. Figure 12 presents the work scene and tracing results.

CONCLUSION

The HIT-WTRS is developed for the welding maintenance tasks in hazardous and inaccessible environment. During the tasks performing, several control modes and used such as stereoscopic vision display based manual control, laser vision sensing based teleteaching and autonomous control, and virtual environment supervisory control. The whole system can be divided into three control loops, which are inner loop, middle loop and outer loop. The system combined HO's global plan capability and robot's local autonomous capability that depends on HO participating in different control loop. Stereoscopic display technology can enhance HO's understand to unstructured environment and increased the localization and tracing precision. The LSVS enhance the system performing capability in unstructured environment, which is not effected by background light source. The experiment results demonstrated performance capability of the system to unstructured environment.

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DIAGNOSTICS OF STRUCTURES USING METHODS OF ELECTRON SHEAROGRAPHY AND SPECKLE-INTERFEROMETRY

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Methods of non-destructive quality control and determination of stress-strain state and residual stresses of welded joints and structures using electron shearography and speckle-interferometry were developed. The compact shearography and speckle-interferometry measuring systems have been created allowing examination of welded structures under the conditions of their manufacture and service. Computer systems for processing interferograms and determination of fields of displacements, deformations and stresses are presented.

Keywords: *electron speckle-interferometry, shearography, non-destructive testing, residual stresses, computer processing*

In the advanced branches of industry (machine building, aircraft industry, space engineering, etc.) the high-strength metals, alloys and composite materials find the wide application. The increase in quality, reliability and serviceability of structures, manufactured of these materials, is indispensably connected with the development and progress of in-process methods and equipment for non-destructive quality control and determination of the stressed state. Usually, these structures operate under the conditions of a complex mechanical effect and temperature gradients. The stress concentration, occurring in the zone of weld defects, reduces the reliability and life of structures.

At present, to reveal defects in materials and structures, a number of methods of non-destructing testing, such as X-ray, radiographic, ultrasonic, magnetic, etc. has been developed [1–3]. It should be noted that none of these methods of non-destructive testing is universal. Each of them has advantages and drawbacks, its field of application, which is defined by the sensitivity and accuracy of detection of defects.

Meanwhile, the engineering practice puts forward the new and new tasks directed to the improvement of serviceability and reliability of structures. To solve them, the new methods of non-destructive testing are required allowing obtaining the in-process and more precise information about the object under examination. Among them are the methods of laser interferometry, such as optic holography, electron speckle-interferometry and shearography.

During recent years the electron shearography is the most rapidly progressing coherent optical method of examination of structures, which is realized using simple optical devices and gives possibility to perform a non-contact examination of the object surface, not damaging it. This method is used in examination of different materials, structures and for measurement of the object deformation under the loading conditions. All this stipulates the non-sensitivity of electron shearography to rigid displacements of the object, caused by effect of environment, thus predetermining its versatility and effectiveness of application in manufacturing [4, 5].

The important advantage of electron shearography for the non-destructive quality control of objects is the fact that it allows revealing the stress concentration, caused by the presence of a defect and design features of the objects, unlike the traditional methods which can only record the presence or absence of defects.

The principle of electron shearography method is as follows. The object being examined is illuminated partially or completely using laser by a light wave which after reflection from its surface enters a shear element, arranged in front of the CCD-camera objective, dividing aperture into two halves. Here, two biased images of the object being examined are appeared in the plane of CCD-camera imaging.

During the interference of light waves the chaotic microinterference speckle-pattern is formed, which is entered to the computer through the CCD-camera. The obtained microinterference speckle-patterns, recorded for two states of the object (before and after loading), are compared and processed to obtain the macrointereference fringes (shearograms).

To perform the non-destructive quality control of elements and sub-assemblies of structures, a compact shearography unit is used, which includes a single-mode laser for illumination of surface of the object being examined, a shearography interferometer forming an object image, CCD-camera for record and transfer of the image and computer for obtaining and processing of interference fringe patterns (Figure 1).

In practical application of shearography for the non-destructive quality control it is necessary to take into account the following assumptions which are resulting from the optical scheme of the shearography unit:

- sizes of objects or object regions under examination should much smaller than the distance from laser to the surface of object being examined;
- a shear element is arranged normal to the object surface, i.e. it maximum approaches the axis of measurements.

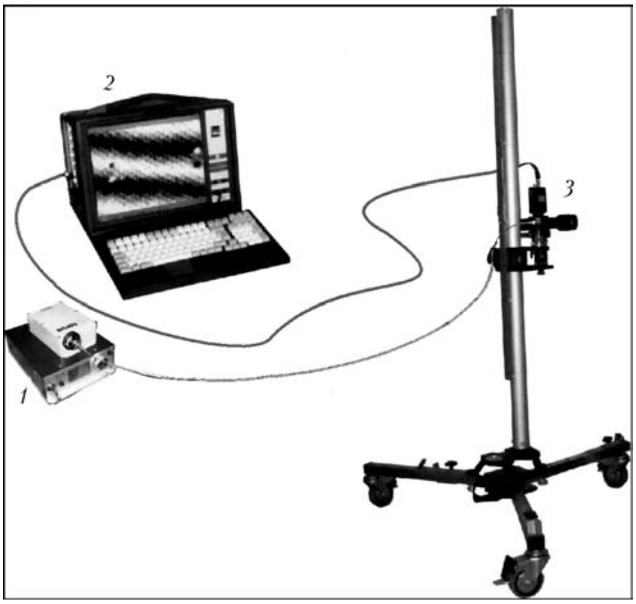

Figure 1. Shearography unit for non-destructive testing: *1* — laser with a light guide; *2* — portable computer; *3* — shearography module

In conductance of the non-destructive quality control the direction of illumination of surface of the object being examined is selected as close as possible to the normal of its surface. In this case the following relationships are used for dark and light interference fringes on the shearogram [5]:

$$\frac{\partial w}{\partial x} = \frac{(2N + 1)\lambda}{4\delta x} \quad \text{(dark interference fringes)}, \tag{1}$$

$$\frac{\partial w}{\partial y} = \frac{(2N + 1)\lambda}{4\delta y}, \tag{2}$$

$$\frac{\partial w}{\partial x} = \frac{N\lambda}{2\delta x} \quad \text{(light interference fringes)}, \tag{3}$$

$$\frac{\partial w}{\partial y} = \frac{N\lambda}{2\delta y}, \tag{4}$$

where N is the order of fringes; λ is the length of wave of laser light source; δx, δy is the shear in the directions, respectively Ox, Oy; $\partial w/\partial y$, $\partial w/\partial y$ are the derivatives from displacements along the normal to the object surface.

The developed technology of shearography non-destructive quality control was used for examination of elements and sub-assemblies of structures, manufactured of different structural materials. The application of this method is also promising for the quality control of thin-walled metal panels manufactured using the arc spot welding.

Usually, the criterion of quality in arc spot welding is the assurance of a required size of the welded spot nugget. It should be noted here that electrode print on the external surface of sheet being welded does not always correspond to the welded spot nugget and, therefore, it is sufficiently difficult to evaluate the quality of the welded spot nugget using the traditional methods.

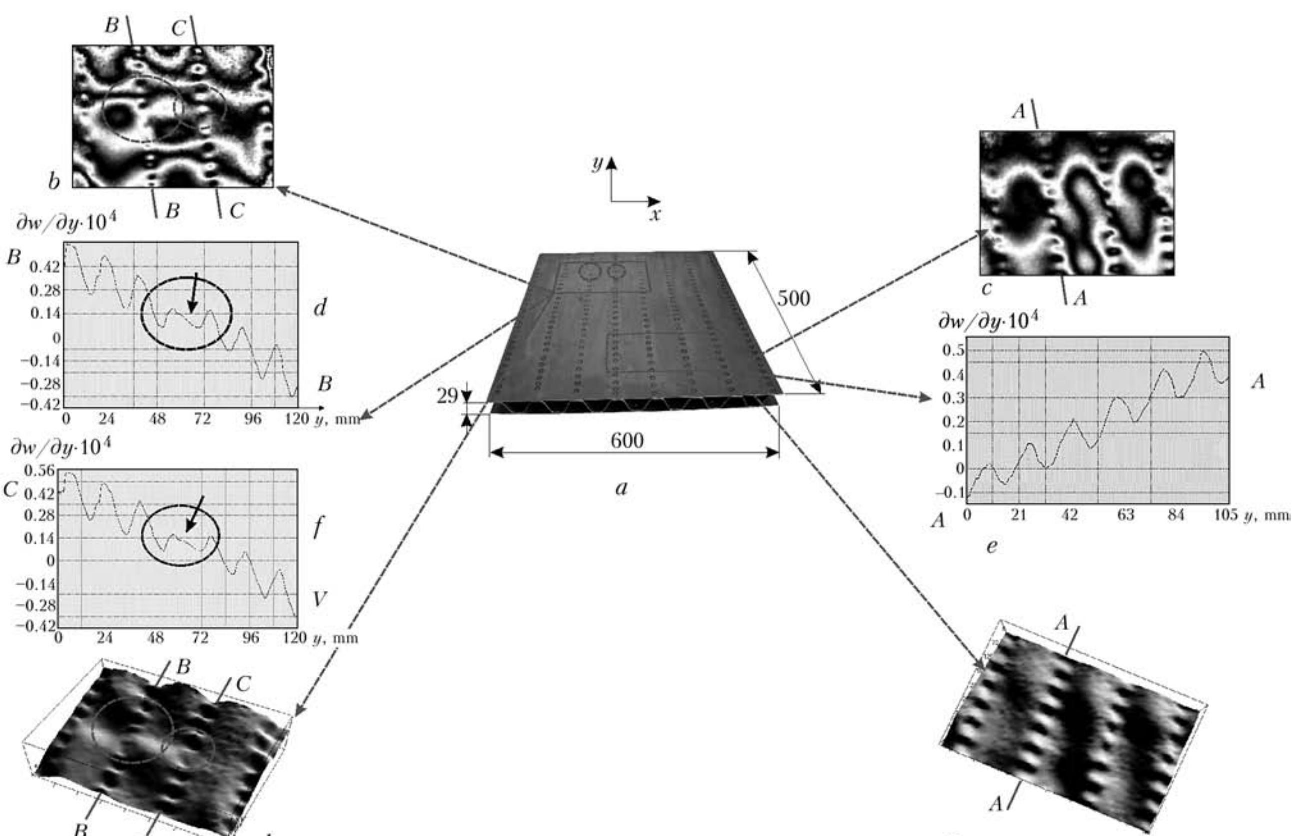

Figure 2. Quality control of panel manufactured by the arc spot welding: *a* — general view of panel; *b*, *c* — interference fringe pattern of region without and with a defect (defect zone); *d*–*f* — distribution of derivative $\partial w/\partial y$ along the selected sections *A*–*A*, *B*–*B*, *C*–*C*; *g*, *h* — three-dimensional patterns of surface deforming

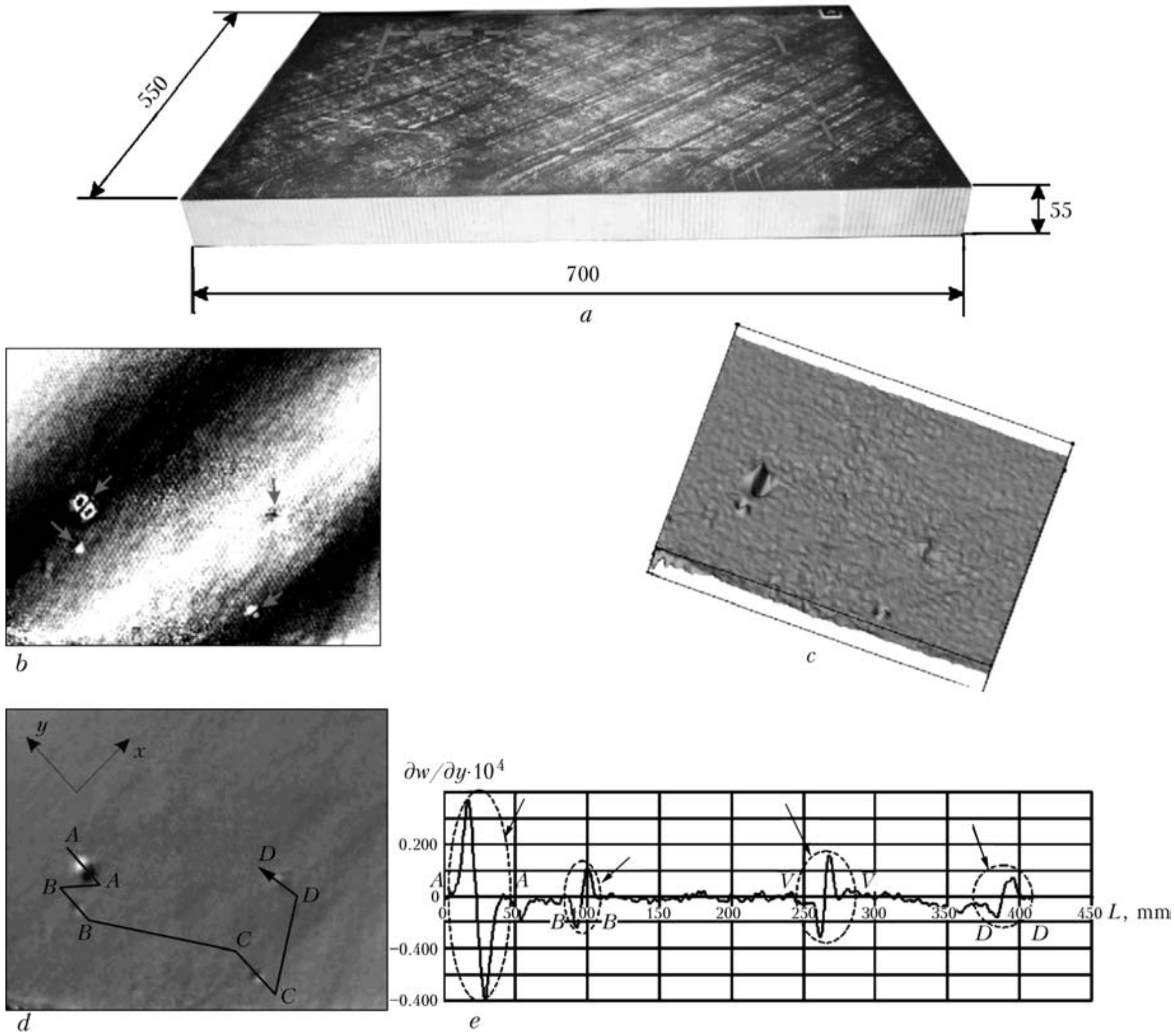

Figure 3. Quality control of element of honey-comb panel using thermal loading: *a* — general view of panel; *b* — interference fringe pattern obtained as a result thermal loading (defect zone is shown by arrows); *c* — three-dimensional pattern of deforming the surface of region being examined; *d* — scheme of examining sections; *e* — distribution of derivative $\partial w/\partial y$ along the selected sections *A–A*, *B–B*, *C–C* and *D–D*

The developed technology of the shearography quality examination allows evaluating the quality of welded spot joints. During experiments, the quality of spot joints of St3 (killed) steel three-layer honey-comb panel structure of 600 × 500 × 29 sizes was examined. The thickness of arc spot welded sheets was 1.5 mm (Figure 2, *a*). To load the panel, the blowing of examining surface with air, heated up to T = 100 °C, was used during 20 s at the distance of 80 mm from the object surface.

The interference fringe patterns, characterizing the areas, respectively, without and with defects, are shown in Figure 2, *b, c*. The plotted three-dimensional patterns of region deforming, respectively, without and with defects, are given in Figure 2, *g, h*. The distribution of derivatives $\partial w/\partial y$ along the selected section *A–A* of region without and with defects in sections *B–B* and *C–C* are shown in Figure 2, *d–f*. The most illustrative is the change of derivative $\partial w/\partial y$ at the region with defects (shown by arrows in Figure 2, *d, f*). Monotony of distribution of derivative in these areas is abruptly changed that proves the absence of the quality spot joint.

The developed technology allows making the in-process quality control of composite honey-comb panels, used in the aircraft industry. The general view of the examining honey-comb panel of glass-reinforced plastic is presented in Figure 3, *a*. During the process of quality control of the honey-comb panel, a light wave, reflected from the panel surface in its initial state, was recorded in the computer memory. To load the honey-comb panel surface, the heating using special infrared lamps was used. Using the computer program, the automatic control of duration of heating the examining panel in its initial state was made. Then, the light wave, reflected from the heated surface of the panel, was also entered into the computer memory. After computer processing of two light waves (before and after heating of panel surface), the fringe pattern (Figure 3, *b*) and three-dimensional pattern of panel deforming (Figure 3, *c*) were obtained. These patterns show the local peculiar features of deforming the examining panel surface on the regions with defects. Figure 3, *e* shows the distribution of derivative $\partial w/\partial y$ along the selected sections *A–A*, *B–B*, *C–C*,

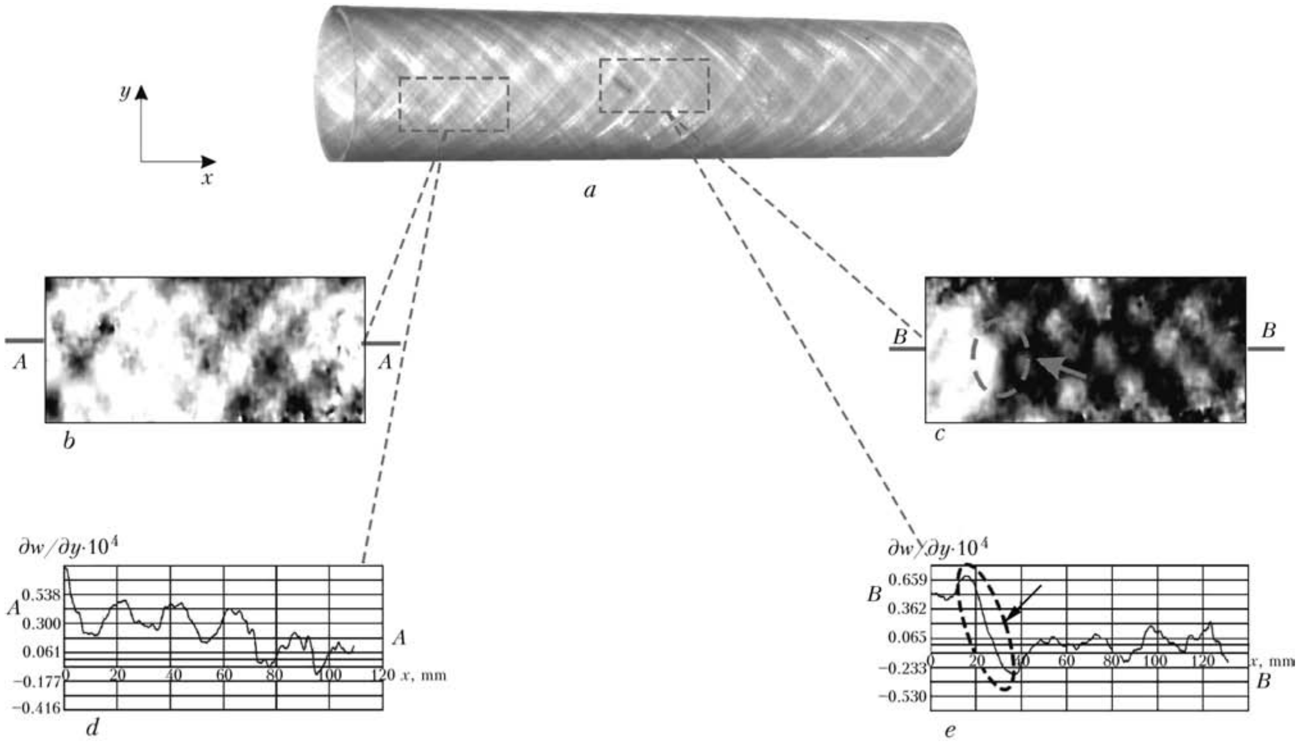

Figure 4. Quality control of glass-fiber plastic tube of 68 mm diameter and 4 mm wall thickness under internal pressure: *a* — general view of panel; *b, c* — interference fringe pattern at the region without and with defects (zone of defect is shown by an arrow); *d, e* — distribution of derivative $\partial w/\partial y$ along the selected sections *A–A*, *B–B*

D–D. On the regions with defects the derivative distribution is abruptly changed.

Using the electron shearography, the quality of thin-walled tubes, made from composite materials, was examined. Experiments were conducted on the quality control of fiber-glass plastic tubes of 68 mm diameter and 4 mm wall thickness. The general view of a tubular element is given in Figure 4, *a*. The shear was made along the axis x, and the internal pressure was created by air for the tube loading. Using the earlier described procedure the reflected light wave, characterizing the state of the examining tube surface, which was loaded by 500 kPa internal pressure, was put into the computer memory. Then, the internal pressure was dropped to 400 kPa and the light wave at this pressure, characterizing the state of the examining surface, was also put into computer memory.

The computer processing of two light waves, reflected from the examining surface, allowed obtaining patterns of interference fringes (Figure 4, *b, c*). Distribution of derivative $\partial w/\partial y$ along the selected sections *A–A* for region without defects and with defects (section *B–B*) showed, respectively, in Figure 4, *d, e*. It was established that the region with defects of 200 mm^2 area was appeared due to fracture of glass fiber at its winding inside the tube wall.

The application of the developed technology of non-destructive testing is effective for examination of carbon composite materials which are widely used in the aerospace engineering. During experiments, a structure element in the form of a truncated cone of 300 × 230 × 200 mm size and 2 mm wall thickness, manufactured of carbon composite material (Figure 5, *a*) was examined. To load the structure element, the blowing of the examining surface with a warm air, heated up to 70 °C, was used during 30 s at the distance of about 50 mm.

Three-dimensional patterns of deforming the regions being examined are shown, respectively, in Figure 5, *b, c*. Here, a local deforming of the examining surface at the region with a defect is seen. Distribution of derivative $\partial w/\partial y$ along the sections *A–A* and *B–B* is shown in Figure 5, *d, e*. In the defective region of the examining surface an abrupt change of derivative $\partial w/\partial y$ is observed (arrow shows an area with a defect). Analysis of obtained results showed that the lamination of composite material of 400 mm^2 area was revealed in the structure element being examined.

The carried out investigations allow making conclusion that the developed technology of non-destructive quality control of structure elements using the method of electron shearography opens up the wide opportunities for revealing defects of different types, which create a local concentration of stresses at a proper loading. The application of this technology in some cases is the only possible variant for obtaining the valid information about the presence of defects in thin-walled structures made of metallic and non-metallic materials.

Residual stresses have a great influence on the serviceability of welded structures. To determine them in elements and sub-assemblies of structures, the methods of tensometry, X-ray and neutron diffraction, magnetic, ultrasonic, laser interferometry, etc. are applied [6–12].

Technology and compact equipment have been developed at the E.O. Paton Electric Welding Institute

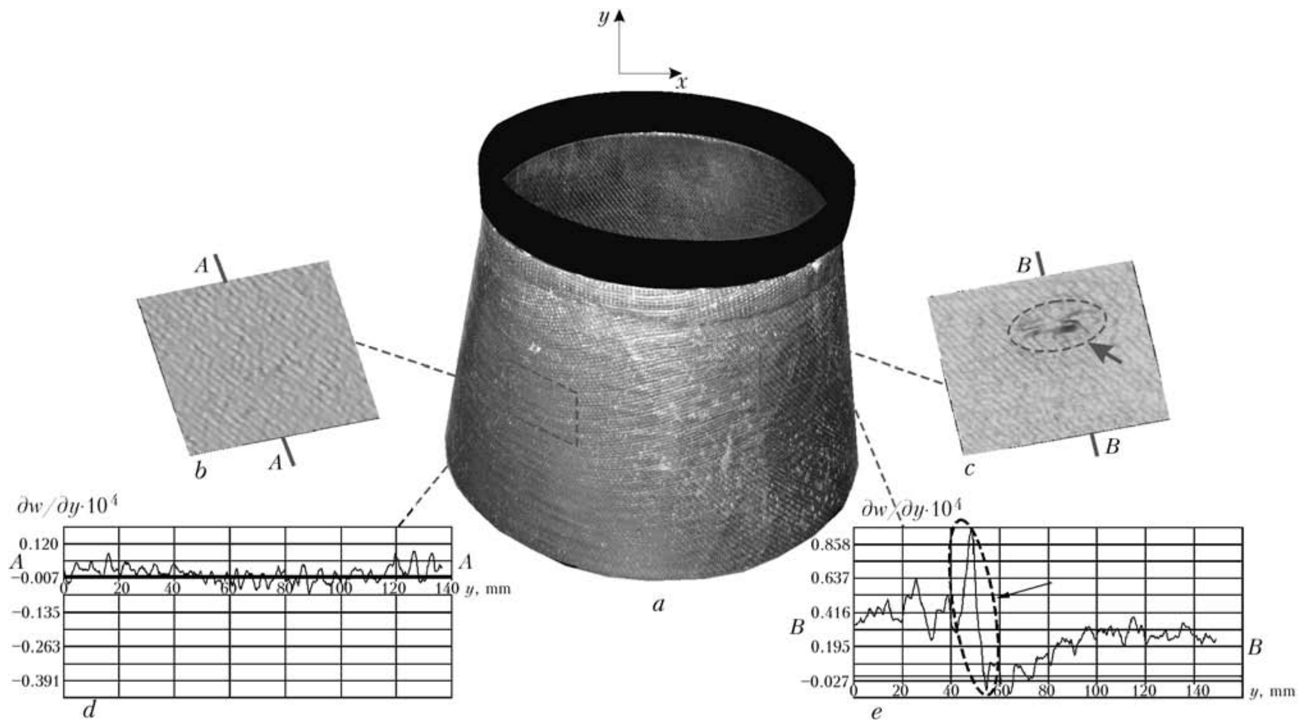

Figure 5. Quality control of a truncated cone of carbon composite material: *a* — general view of cone; *b*, *c* — three-dimensional patterns of deforming the surface of region without and with a defect; *d*, *e* — distribution of derivative $\partial w/\partial y$ along the selected sections *A–A*, *B–B* (zone of defect is marked)

for the in-process determination of residual stresses using the method of electron speckle-interferometry with a blind hole drilling [13]. This method is based on use of an optic scheme of the interferometer, given in Figure 6, that allows measuring the plane displacements. Laser beam *1* is divided by a divider *2* into two beams (50/50), which by means of mirrors *3* and *4* enter the lens *5* and *6*, are broadened and illuminate the object symmetrically under angle θ with respect to normal to the surface of the object *8* being examined. In conducted experiments θ was equal to 57°. The light wave, reflected from the surface, carries information about the condition of the region being examined and then through the CCD-camera *7* enters computer *9*, in which a board of digitization is arranged. The image is digitized and processed up to obtaining on the monitor of the interference fringe patterns around the drilled hole.

The application of the given symmetric optic scheme of a speckle-interferometer allows measuring a plane component of vector of displacement $u(x, y)$ by formula from work [14]:

$$u(x, y) = \frac{\Phi(x, y)\lambda}{4\pi \sin \theta}, \qquad (5)$$

where $\Phi(x, y)$ is the optical difference of phases caused by drilling of a blind hole in the object region under examination.

To determine the optical difference of phases $\Phi(x, y)$ in points of surface of the object being examined, a method of phase pitches, i.e. record of several interferograms with a known shear of phases between them, is used [15]. Then, according to this method, a system of non-linear equations is composed, whose solution is the distribution of phase in each point of the surface.

For practical realization of the procedure (Figure 6), a piezo-control mirror *4*, mounted in one of optical arms of a speckle-interferometer, is used. Control of a piezo-element *11* is realized by voltage supply to it from the output of digital analog converter *10*. The change in voltage, supplied to the piezo-element, causes the reciprocal displacement of the mirror, which is fixed on its surface, that leads to the change in the interference fringe pattern by a definite value of a phase over the entire field of observance. This value is directly proportional to the change in voltage supplied to the piezo-element.

To determine the residual stresses in elements and sub-assemblies of structure using the described optical scheme, a small-sized unit has been developed which is mounted directly on the surface of object under examination (Figure 7).

The measurements are made in the following sequence. The speckle-interferometer is mounted on the object surface. The reflected light wave characterizing the initial state of the area examined is converted through the CCD-camera into an analog signal, which is put into the computer memory. After elastic relieving of stresses by drilling a blind hole of 1.0–1.5 mm diameter and 0.4–1.5 mm depth the light wave is similarly put into the computer memory. After the computer processing of data the interference fringe pattern, arranged around the hole, is appeared about these two light waves on the monitor. It contains information about values of residual stresses in an examined point of the object.

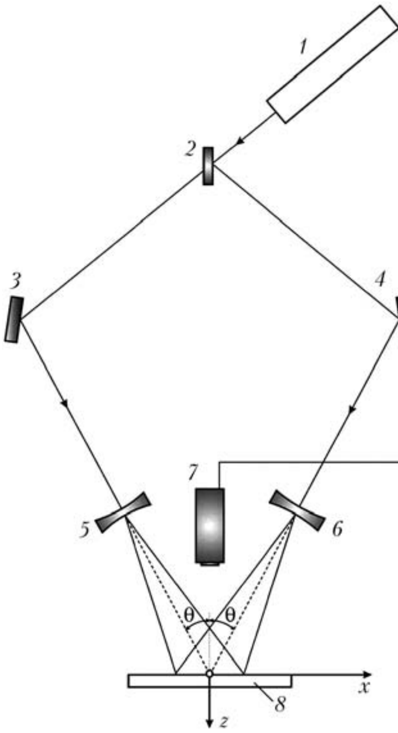

Figure 6. Optical scheme of speckle-interferometer for measurement of plane components $u(x, y)$ of vector of displacements: *1* — helium-neon laser; *2* — optical divider 50/50; *3, 4* — flat mirrors; *5, 6* — lens; *7* — CCD-camera; *8* — object being examined; *9* — computer; *10* — controller; *11* — piezo-electric converter

For plates with a through hole, which is located in a field of stresses, the values of displacement of points on the object surface around the hole can be calculated using the relationships obtained in work [12]. As the similar task for plate with a blind hole has no analytical solution, then the empiric formulae, given in work [16] are used. The dependence of displacements u_r and u_θ, occurring as a result of relieving stresses σ_{xx}, σ_{yy} and τ_{xy} at some distance r from the hole center, on angle θ has the form of

$$u_r(r, \theta) = A(\sigma_{xx} + \sigma_{yy}) + + B[(\sigma_{xx} - \sigma_{yy}) \cos 2\theta + 2\tau_{xy} \sin 2\theta]; \qquad (6)$$

$$u_\theta(r, \theta) = C[(\sigma_{xx} - \sigma_{yy}) \sin 2\theta - 2\tau_{xy} \cos 2\theta], \qquad (7)$$

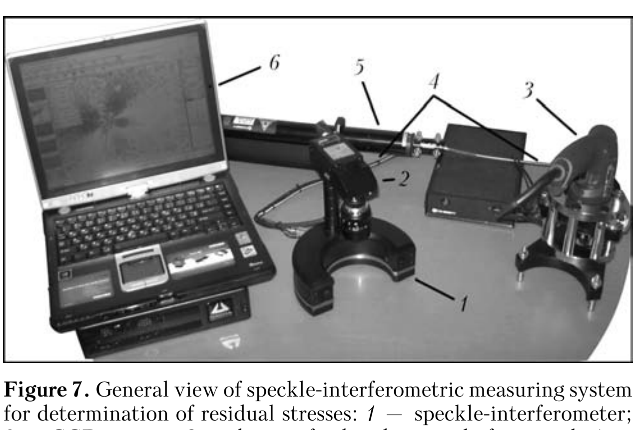

Figure 7. General view of speckle-interferometric measuring system for determination of residual stresses: *1* — speckle-interferometer; *2* — CCD-camera; *3* — device of a dosed removal of material; *4* — light guide; *5* — laser; *6* — computer

where A, B and C are the empiric coefficients, depending on mechanical properties of material, distance from the hole center to the point of measurement, its diameter and not depending on the kind of stressed state.

To determine experimentally the coefficients A, B and C, the procedure and equipment have been developed. The procedure supposes a creation of a uniaxial stressed state in a special test specimen with a known level of stresses. A hole was drilled in the loaded specimen and measurement of components of vector of displacements was made using a speckle-interferometer in its zone. The values of empiric coefficients were calculated in the examined points from the data about displacements. They were also determined using the method of finite elements by the developed algorithm for additional check-out. The obtained results showed that the results of numerical determination of values of coefficients A, B and C are well correlated with experimental values.

The developed procedure supposes the measurement of a component of displacements $u_x(r, \theta)$ at a constant distance from the hole center. Using equations (6) and (7), u_x can be presented in the form of

$$u_x(\theta)\,|_{r = 2.5r_0} = F(\theta)\sigma_{xx} + G(\theta)\sigma_{yy} + H(\theta)\tau_{xy}, \qquad (8)$$

where

$$F(\theta) = (A + B \cos 2\theta) \cos \theta - C \sin 2\theta \sin \theta,$$
$$G(\theta) = (A - B \cos 2\theta) \cos \theta + C \sin 2\theta \sin \theta,$$
$$H(\theta) = 2B \sin 2\theta \cos \theta + 2C \cos 2\theta \sin \theta$$

are the functions depending on coefficients A, B and C and angle θ.

The determination of residual stresses by the suggested method is carried out in the following sequence:

- at the distance of $2.5r_0$ from the center of drilled hole of radius r_0 the points under an arbitrary angle relative to axis of illumination are selected and displacements are measured on the surface of the object being examined using a speckle-interferometer;
- components σ_{xx}, σ_{yy} and τ_{xy} of tensor of stresses are calculated by the method of least squares from the data about displacements using (8);
- values of main stresses σ_1, σ_2 and angle η between the axis of illumination of speckle-interferometer and direction σ_1 are determined by formulae

$$\sigma_1, \sigma_2 = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{\left(\frac{\sigma_{xx} - \sigma_{yy}}{2}\right)^2 + \tau_{xy}^2};$$

$$\eta = \begin{cases} \frac{1}{2} \tan^{-1}\left(\frac{2r_{xy}}{\sigma_{xx} - \sigma_{yy}}\right) & \text{if } \sigma_{xx} > \sigma_{yy}, \\ \frac{\pi}{4} & \text{if } \sigma_{xx} = \sigma_{yy}, \\ \frac{\pi}{4} + \frac{1}{2} \tan^{-1}\left(\frac{2r_{xy}}{\sigma_{xx} - \sigma_{yy}}\right) & \text{if } \sigma_{xx} < \sigma_{yy}. \end{cases}$$

To evaluate the accuracy of measurement of plane displacements using a small-sized speckle-interferome-

Results of determination of residual stresses along the sections *I*–*IV*

R, mm	Radial σ_{rr}, MPa	Circumferential $\sigma_{\theta\theta}$, MPa
	I	
112	6	218
122	29	196
132	37	165
195	55	125
202	83	128
282	28	−138
292	44	−128
302	43	−121
	II	
122	23	195
132	43	166
142	23	154
195	56	145
202	89	141
282	38	−143
292	57	−126
302	38	−136
	III	
112	2	231
122	11	209
132	32	180
195	40	155
202	89	149
282	41	−159
292	34	−150
302	38	−116
302	38	−117
	IV	
122	29	216
132	28	178
142	40	163
195	49	145
202	75	143
282	57	−136
292	32	−124
302	43	−104

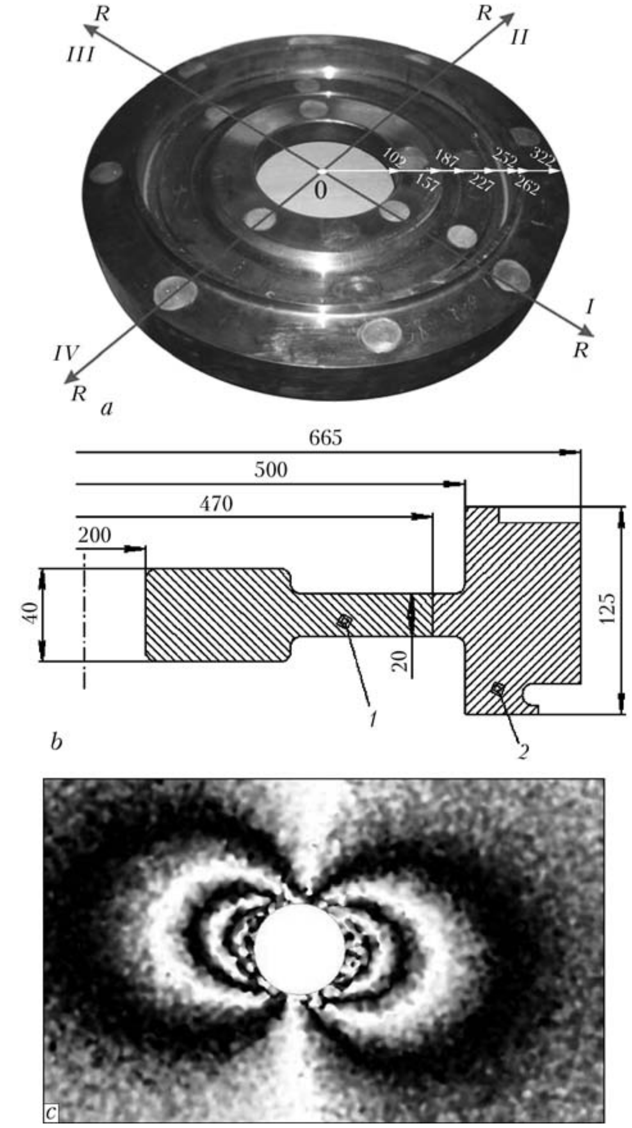

Figure 8. General view (*a*) and geometric sizes (*b*) of gas turbine engine rotor disc and typical pattern of interference fringes around the drilled hole (*c*): *1* — hub; *2* — rim

ter and automatic computer processing of interferograms, the solution of a known problem about bending of a console beam with a sealed end by a force to a free end was used. Experiments showed that deviations of values of stresses, which were determined by speckle-interferometry method, from calculated ones, did not exceed 5 % of yield strength of the material being examined [17].

The method of determination of residual stresses and designed equipment were used for examination of the residual stressed state of a welded disc of the gas turbine engine rotor. The disc was manufactured from chromium-nickel steel of a martensitic type 07Kh12NMBF-Sh (EP-609Sh), used in turbine construction, and composed of two parts: hub *1* and rim *2* (Figure 8, *b*), which were joined by welding. The disc is operated under action of high loads and temperature, causing the creep of the disc material, and distribution of temperatures, non-uniform in radius and non-constant in time, stipulating the superposition of temperature stresses, changing often periodically in time. To increase the serviceability of the rotor disc, the new technology of its manufacture using electron beam welding has been developed. Owing to a narrow and deep penetration, also to a small heat-affected zone, the required strength characteristics of the disc are provided.

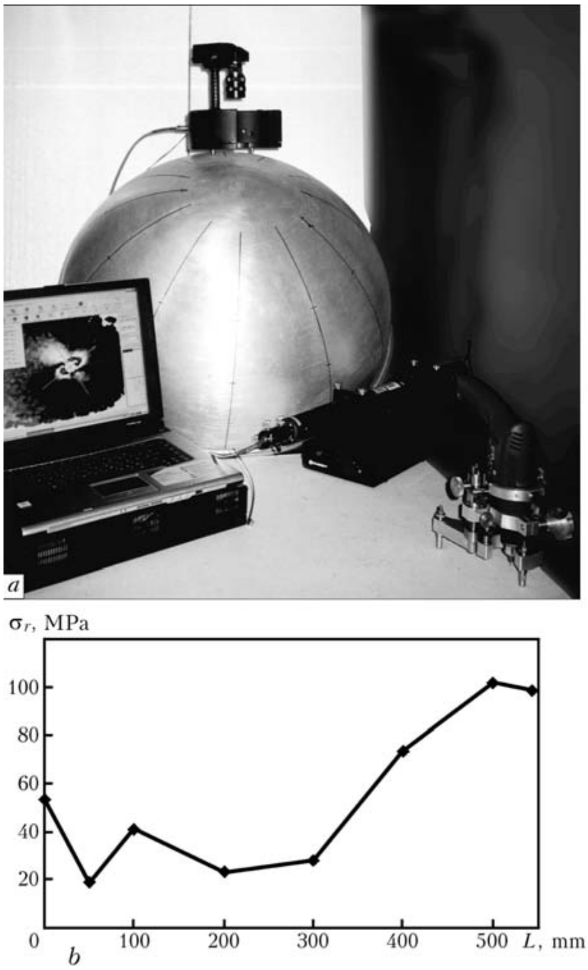

Figure 9. Appearance of a semi-spherical shell of variable thickness (*a*) and distribution of residual stresses σ_r along its generatrix L (*b*)

The residual stresses were determined in sections *I–IV* (Figure 8, *a*) in points located at different distances R from the disc center. The values of calculated residual stresses are given in the Table. The typical interference fringe pattern around the drilled hole is presented in Figure 8, *c*.

Analysis of the obtained results showed that the residual stresses on the surface of hub and rim are distributed non-uniformly. Unlike the hub, the compressive stresses are acting on the rim surface, that affects favorably the disc serviceability. The technology of manufacture of the turbine rotor welded disc using electron beam welding ensures the meeting requirements of standard documents to the disc strength and does not lead to occurrence of high residual stresses.

The developed procedure of determination of residual stresses was used also for investigation of technological stresses which occurred in manufacture of aluminium alloy semi-spherical shells of 760 mm diameter and variable thickness, which are used in aerospace industry (Figure 9, *a*). The curve of distribution of residual stresses σ_r along the generatrix is given in Figure 9, *b*. Basing on the analysis of results of investigation of the mentioned stresses, the technology of manufacture of shell structures, where the minimum residual stresses are formed, was updated.

Thus, the developed method and equipment for determination of residual stresses in elements of thin-walled structures, based on the method of electron speckle-interferometry in combination with a probing hole, allows quick and precise examination of distribution of stresses over the surface of objects being examined, that opens up the wide opportunities for diagnostics of the stressed state under laboratory and industrial conditions.

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EDUCATION AND TRAINING IN WELDING AND TESTING OF MATERIALS

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The education according to the IIW system which is internationally approved is the striking example of reorganization and harmonization of national and international standards on the personnel qualification. The preparation technique is continuously improving through the teaching conceptions which are supported by multimedia and Internet. Ever more complicated multimedia technologies require opportunities of similar teaching of qualified personnel also in the field of testing technology.

Keywords: *welding, material testing, welding technologies, personnel, teaching methods, qualification, certification*

Education and career are the two sides of a coin. In technology this need not be expressly communicated since from the origin of handicraft it has been known that, on the one hand, a good apprenticeship is the basis of sound skills and, on the other hand, it is the skilful craftsman, who often obtains an economic success. To this end, craftsmen have been travelling around after their apprenticeship, in order to learn new methods and working skills.

In industry, too continuous further education is the basis of success. This has mainly been proven by those companies that have been successful for many decades.

But also in other sectors such as sport or the show business success does not appear from nowhere but requires a sound education. This fact cannot be obscured by doping scandals or doubtful casting shows. Even comedians and politicians mostly either avail of comprehensive education by university studies, of language skills or an excellent general knowledge. At least this is valid for those who have been successful over a long period of time.

For technology in particular it is valid that education must be proven through an approved qualification and often through certification. The welding and testing technology in this regard serves to be a pioneer. On the other hand these technologies have to meet special demands concerning the safety of technical products.

IIW and EWF education. The starting point of the currently existing education and training system in the IIW (International Institute of Welding) and EWF (European Welding Federation) has been a proven system with a tradition in welding education in Germany. This has its base in the DVS and their predecessors and has been entered into practice by the welding and training institutes, the oldest of which having a more than 80 years tradition as well as by a variety of other institutes of education. On the field of trades, the system is based on the education as a skilled worker with a welders' certificate in different processes or in case of university studies on basic studies in engineering or currently as a bachelor or master in a technical subject.

Whereas it was a process of European harmonisation first, it has changed into an international system in the last few years. For the IIW founded in 1947 first the exchange of scientific-technological research result was focussed on. The educational system of today is based on the work carried out in the EWF in the 80's and 90's.

The educational system alone is not the basis of success. As shown in Figure 1, education has to be understood as a firm constituent of quality assurance. You can see in the Figure that despite of all technical influences the human factor still is of high importance for the quality and reliability of products.

Therefore, the requirements of education and qualification in welding are a constituent not only of national but also of international standards as shown in the Table. In many technical standards, one of them being the standard DIN 6200-2 «Welding of rail vehicles», reference is made to existing international regulations that describe requirements on personnel. Other joining processes, too, orient themselves at this system of quality assurance such as the adhesive bonding technology which, like welding, is characterised as a specialised process.

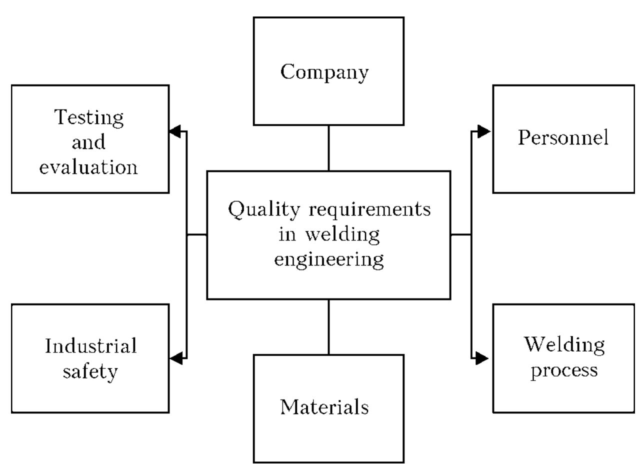

Figure 1. System of quality assurance in welding engineering

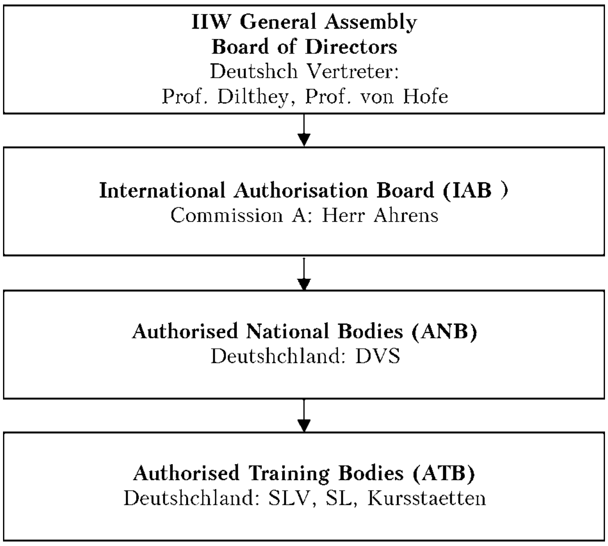

Figure 2. Bodies of the IIW and their German representatives and national implementation (date of issue: 31.07.2007)

International qualifications. It is not worth harmonising all educational measures on an international scale. Rather, it is more important to set essential benchmarks of quality assurance by training programmes and certificates. To this end the following qualifications of the IIW exist: International Welding Engineer; International Welding Technologist; International Welding Specialist; International Welding Practitioner; International Welding Inspection Personnel; International Welding Designer; International Welder.

After having passed one of these types of qualification a certificate of the IIW will be issued, thus giving companies offering welding applications the opportunity of a basic orientation when recruiting and evaluating personnel. It is of particular importance into wide branched multi-national range of sub-suppliers which is valid for both, qualification of the operating personnel, the welding coordinators, and inspectors.

Through different bodies of the IIW, it is guaranteed to secure and further develop the existing quality and its national implementation as shown in Figure 2. This Figure also shows that Germany is well represented within the organisation of the IIW.

Today, the IIW sets an internationally comparable standard to education and training. It must be stated, however that those standards have not been implemented to the same extent in all the countries. Thus, most of the welding engineers are still being educated in Germany which is not in correlation with the number of inhabitants and shows the different implementation in the national industries.

By means of audits it is assured that the requirements on the educational institutes adopted by the IIW are complied with. As far as comparability is concerned these requirements represent an average value which can be fulfilled by the education institutes. The different scope of equipment available as well as the experience of the teachers alone make the existing differences even more distinctive.

European and international standards with reference to requirements on education

Assignment	ISO	EN
Welders examination	9606	287
Welding coordinators	14731	719
Quality assurance	3834	729
Non-destructive testing	9712	473
Steel construction		1090
Machine operators	14732	1418
Diving welding	15618	15618
Rail vehicles		15085
Unfired pressure vessels		13445

In addition to the opportunities given by the IIW, the EWF has developed different training units harmonised European wide: European Thermal Spraying Specialist; European Thermal Spraying Practitioner; European Thermal Sprayer; European Adhesive Engineer; European Adhesive Specialist; European Adhesive Bonder; European Welding Specialist for Resistance Welding; European MMA Diver Welder; European Plastics Welder.

According to the demands of a strong national industry the DVS supplements the internationally approved scope of education by further education opportunities.

Distance learning and blended learning. Founded on a solid base of IIW regulations, it is necessary to meet the requirements of industry and to develop new educational concepts. To this end, the objective is to teach knowledge ready to enrolment at a minimum expenditure of time.

In order to obtain this, the GSI began as early as in the year 2001 to educate in the form of multi-media teaching. The so called CBT (Computer Based Training) enables the participant to gain knowledge him/herself on the PC. Beside of the common explanations in the form of text and figures, there are also animations and video sequences thus securing a high extent of audiovisual aids. Every teaching unit is completed by a test on the knowledge showing the results of the studies. Together with his/her application to the training course, the participant obtains the possibility to participate in an Internet chat and to exchange his/her questions with tutors via e-mail.

Homework to be done independently with the opportunity to have it corrected complete the positive learning effects. The final exam will then be carried out in the classical way. This form of teaching was first applied for a qualification of welding engineers, part 1. Part 2 of the education is carried out in the form of a practical training and therefore is to be carried out as classroom learning in the form known. Here, the participants get familiar with all common welding processes. Supplementary to the CBT-concept the education programme of blended learning has been introduced for the education of a welding engineer, part 3. This is a combination of classroom learning and self-study. Since its introduction to the market in 2005 more than a hundred participants have been educated.

Within the GSI mbH the SLV Duisburg as the headquarters for distance learning courses offers this type of education. Upon request of the participants, classroom learning phases are also offered in other SLVs.

The use of multi-media education methods as well as their combination with Internet supported supplementary education lead to a higher extent in assistance for the training institute, but for the participant the following advantages will result: individual timing of the training; individual speed of progress; avoidance of travelling and accommodation expenses.

The special advantage for the employer is given by the true execution of the training accompanying the job which is the decisive advantage concerning the high cost of personnel.

Since communication via the Internet is not bound to economic borders, the execution of the training course as a CBT and a blended learning course may as well be offered on an international scale. Using the English version the welding engineers may be qualified world wide.

New methods — the welding trainer. Not only in theoretical education but also in practical training basic structures having remained unchanged for 40 years must be reconsidered. To his end, the influence on the welders and their handicraft skills are versatile in character. Therefore, the following must be considered: further development of welding equipment in general and in particular of electric power sources; changes in working protection; material properties (base metal, filler metal, gases); increasing productivity within the company; specialisation of products.

Moreover, the question must be raised for training institutes as to how the education times and costs can be reduced at an improved quality of the education. Furthermore, the educational organisation must assure that the participants may commence their training any time. For the teachers this means an almost 100 % individuality when performing the training course.

In order to meet these demands, a glance should be taken to other fields. Thus, in competitive sports complex motions are separately trained. Principally, this is possible in welding, too.

In a common research project with the Paton Institute in Kiev therefore the foundation of a system of device called «welding trainer» has been laid (Figure 3). Using the «welding trainer», the basic capabilities of arc welding are trained without already striking the high performance arc. The three dimensional guidance of the torch is electronically controlled and the welder will be asked by a signal and audio voice unit to carry out corrections. The pilot arc used in the process simulates the actual process and particularly trains the welder in striking the arc. With each weld a supervision of the parameters is performed which could be taught by a welding training in an individual training only. The range of parameters present at the end of the welding shows in summary the consistency of the movements. Not before an intermediate result has been obtained, the training «in safety» is ended and the welder changes to high performance power sources. To this end, he carries out the movements, he is already capable to thus being able to concentrate on new focuses such as the high performance arc and formation of the weld pool.

Figure 3. Training of manual skills when welding on the «welding trainer»

Through this procedure it is also avoided that mistakes might creep in during the movements that later can be corrected at a large expense only. The extent of assistance is also improved when welding trainers are used. Initial mistakes will be reduced and the processes split into individual complexes which the welder can better concentrate to.

Education on the field of material testing. Welding and material testing directly belong together when manufacturing a product. This is particularly valid for safety relevant constructions such as bridges, rail vehicles, ships or pressurised vessels.

Based on this correlation, the idea has resulted to implement the competences in welding processes into the performance of education and training of material testers. The special requirement is the design of the weld capable to be tested which is realised in the training courses. These certificates may either be obtained according to EN 473 or the qualification as an European Material Tester and Material Tester with an examination by the chamber of industry and commerce (IHK). In particular the non-destructive methods of material testing are within the focus. Besides of the courses for radiographic testing; ultrasonic testing; visual testing; magnetic particle testing; eddy current testing, there are also special offers based on our own developments and experience.

Based on ultrasonic testing, a process has been developed where residual gaps in welded structures can be quantitatively evaluated. This enables both,

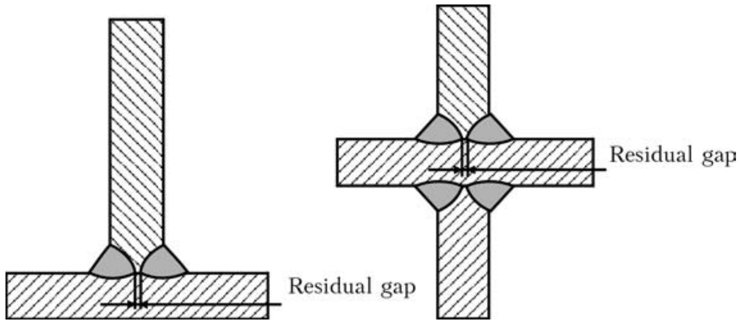

Figure 4. Shapes of seams with demand on quantitative determination of the residual gap

in design and in manufacture simplifications therefore the reduction of costs. In principle, testing is based on a comparative measurement whose exactness is assured by a special sequence of tests. Figure 4 shows possible shapes of seams where the quantitative measurement can be applied.

A further method requiring a special demand on training is the determination of cracks under coatings. Here, a modified eddy current testing can be used. The advantage is the execution of the examinations with a large extent of standard equipment. However, during the education the trainer must interpret the tests. This procedure has successfully been applied with the evaluation of cracks under zinc coatings.

International education. German companies compete well on the international market. These are not only large-scale enterprises but also medium-sized enterprises. The quality of the products is of decisive importance for their existence, thus being assured by the education and training of the staff.

For educational institutes this means a challenge with regard to efficiency of the education, the conditions of admission of the participants as well as considering particularities specific to certain countries. Summarized it can be stated that German companies expect the same quality of the education worldwide when co-operating with a German training institute.

The execution of such educational measures extends from a project-related training up to a continuous education in our own offices abroad.

In the following you will find some examples: advice on the setting up of an SLV/SK (China, Vietnam, Cuba, Sudan); investment in own institutes (Poland, Czech, Egypt); execution of training courses (Vietnam, China, Austria, Malaysia, Indonesia, Libya, Turkey, Greece); licensing of distance learning courses (The Netherlands, Italy, Switzerland, Austria); distance learning courses (SFI); training in Germany in English language (SFI); International conferences (International conference on Spraying).

Summary. Through the international system of training and education of the IIW, welding engineering offers a unique comparability of the training contents and qualifications. Thus, a contribution is made to the acceptance of welding engineering. For the quality assurance in multi-national projects the IIW has a unique position.

New methods of education by distance learning course, blended learning or the training device «welding trainer» are those contributions of the GSI made to a further development of the methodical competence.

Since welding engineering considers itself as being embedded into more and more complex entire processes, education in welding, too must consider interdisciplinary subjects to other industrial sectors. These are among others the education on the field of material testing as well as the education in corrosion protection. The training and further education of designers on the field of welding technology is also paid special attention to.

Eventually, a modern education presupposes a close relation to the general state-of-the-art of science and technology. To this end, the network of the DVS and in particular the elevated competence of university research institutes in Germany offer the best opportunities which are recognised and approved by internationally operating customers.

CORROSION CRACKING OF CHROMIUM-NICKEL STEELS IN HIGH-PARAMETER WATER

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The results of investigations of effect of oxygen and chlorine-ions on the susceptibility to corrosion cracking of chromium-nickel austenite steels in high-parameter water are given. For separate steels the results of tests in boiling water solutions containing 42 % $MgCl_2$ and 40 % $CaCl_2$ are given. The possibility for increase in service life of equipment and pipelines of reactor plants using austenite steels with high content of nickel and austenite-ferrite (duplex) steels due to their much higher resistance against corrosion cracking in cooling water media is shown.

Keywords: *high-alloyed steels, welded joints, equipment and pipelines of NPP, operating pressure, technological loads, residual welding stresses, corrosion cracking, service life increase, new induction materials*

During service of NPP equipment and pipelines of chromium-nickel austenite steels 08Kh18N10T, 304 (18.5 % Cr–9.5 % Ni), 316 (17 % Cr–12 % Ni–2.5 % Mo), 321 (18 % Cr–10 % Ni–Ti) and 347 (18 % Cr–11 % Ni–Nb) the cracks were observed in base metal and welded joints. Their initiation is attributed to the prone of steels to stress corrosion cracking (CC). The minimum time before cracks initiation, fixed using radiographic control, is approximately 4 years, and their growth across the pipe wall is on average 7–10 years.

During service the equipment and pipelines are loaded with internal pressure, own weight and forces caused by temperature displacements. Moreover, in the welded joints, performed without subsequent heat treatment, residual welding stresses are available. The high level of stresses contributes to corrosion cracking of steels in a high-parameter water. The propagation of these cracks has a branched intercrystalline nature with a developing with respect to axis of pipelines in longitudinal and perpendicular directions, this resulting in large extension and considerable volumes of metal damage.

Such defects were for the first time revealed in practice of service US NPP in welded joints of pipelines of «boiling» reactors (BWR) manufactured from non-stabilized steels 304 and 316. The pipelines of BWR units (Germany), where similar cracks were revealed in the welded joints, were manufactured of austenite chromium-nickel steels 321 and 347, stabilized with titanium and niobium, respectively.

During service, the damage of heat exchange pipes of vertical and horizontal steam generators of NPP is observed. The results of metallographic examinations of damage nature are the evidence of the fact that the mechanism of pipes damage is also stress CC (Figure 1). The damages of heat exchange pipes and pipelines of steel 08Kh18N10T were also observed at the stage of erection works on the coastal platforms. With accumulation of chlorides due to humidity condensation from the sea air, the cracks occurred on the surface of pipes in sources of a local pitting corrosion.

Thus, the manifestation of susceptibility of 08Kh18N10T steel and its analogies (steels 304, 316, 321 and 347) to CC is the problem for equipment operating in contact with water environment.

The procedure of investigations. To define the parameters of water (temperature, impurities content), promoting the tendency to CC to the highest extent, the autoclave tests of specimens of 08Kh18N10T steel under the conditions of tension at a low rate of deformation were performed. For the further investigations the temperature of water in autoclave was selected, at which the value of transverse reduction in area Z in test specimens was minimum. The effect of parameters of heat-transfer medium on susceptibility of steels to CC was investigated also by testing statically loaded (bent by 180°) plane U-specimens in autoclaves with desalted water at high temperatures and equilibrium pressure (7.5 MPa). In experiments the initial concentration of oxygen and chlorine-ions, dissolved in water, was varied. The resistance criterion against stress CC was the time before

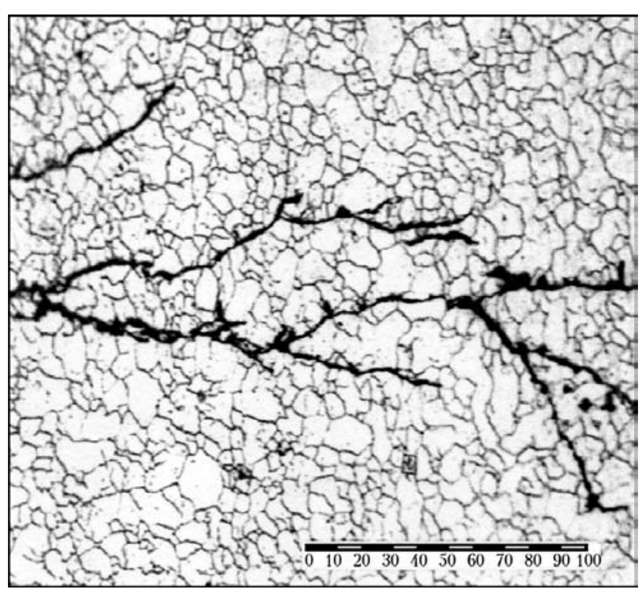

Figure 1. Microstructure of heat exchange pipes of steel 08Kh18N10T with the characteristic corrosion cracking

cracks initiation. To estimate the steels tendency to CC the published results of tests in boiling water solutions containing 42 % $MgCl_2$ and 40 % $CaCl_2$ were used. The metallographic examinations of microstructure of metal of test specimens in the zone of fracture were carried out to reveal the nature of cracks.

Investigation of corrosion cracking of steel 08Kh18N10T. The results of autoclave tests in high-parameter water under conditions of tension at a low deformation rate are the evidence of 08Kh18N10T steel tendency to delayed deformational CC. Here, the steel susceptibility to this corrosion type is manifested at a certain combination of temperature and concentration of oxygen and chlorides dissolved in water (Figure 2).

In specimens, tested in water at temperatures of 250–340 °C, a great reduction in value of reduction in area *Z* is typical, especially noticeable at the temperature of 290 and 300 °C. Under these temperature conditions at the initial oxygen concentration of 7.5–8.0 mg/kg the *Z* value of fractured specimens does not exceed 30 %. The fracture is accompanied by formation of secondary circular cracks of a corrosion nature on the cylindrical surface of specimens. At the temperature above 300 °C the values of transverse deformation of specimens before their fracture are abruptly increased by more than 50 %. It should be noted that the values of transverse reduction in area of specimens, found during autoclave tests, were lower in all the cases as compared to tests at the same temperatures in air.

When adding 5 mg/kg Cl^- water, containing 7.5–8.0 mg/kg O_2, the remarkable decrease of *Z* in specimens is observed in the wider temperature range. Even at 350 °C the presence of chlorine ions negatively affects the 08Kh18N10T steel resistance against the delayed deformational CC.

In the water with an initial oxygen concentration of 3.5–4.0 mg/kg the 08Kh18N10T steel preserves the general nature of ductility dependence on the temperature with maximum its decrease at 250 °C. Here,

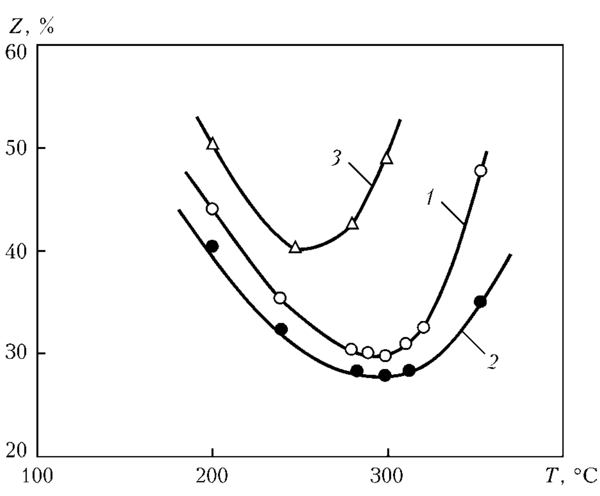

Figure 2. Effect of oxygen and chlorine-ions on ductility of steel 08Kh18N10T: *1* — 7.5–8.0 mg/kg O_2 + 1 mg/kg Cl^-; *2* — 7.5–8.0 mg/kg O_2 + 5 mg/kg Cl^-; *3* — 3.5–4.0 mg/kg O_2 + 1 mg/kg Cl^-

the temperature range of susceptibility to brittle fracture is narrowed and displaced towards lower values. The level of effect of environment on the steel ductility drop is also significantly lower.

During the tests according to the GOST 6032 (AM method) the 08Kh18N10T steel does not manifest the susceptibility to the intercrystalline corrosion (ICC). However in all cases the cracks propagation in the fracture regions of specimens, tested in high-parameter water under tension at a low rate of deformation, has an intercrystalline or mixed nature. Under conditions, causing the susceptibility to a delayed deformational CC, the fracture surface of specimens contains a large fraction of brittle fracture and the sources of cracks initiation around the entire perimeter of section.

The results of corrosion tests given above prove that 08Kh18N10T steel, not susceptible to ICC, can show the tendency to intercrystalline corrosion fracture (ICF) in high-parameter water even after provoking heating at 650 °C. The service damages of pipelines of steels 321 and 347, not susceptible to ICC, can also be subjected to the formation of intercrystalline corrosion cracks due to the presence of elements-stabilizers (titanium, nobium) in their content. The fractographic examinations of metal fractures in the damaged regions of pipelines are the evidence of grain boundary nature of fracture. That gives grounds to suppose that autoclave tests in high-parameter water at a low deformation rate are close to the service conditions of pipelines at NPP.

The non-stabilized steels 304 and 316 are in a sensitized state after heating at the temperature range of 550–650 °C and prone to ICC. Under the conditions, promoting the stress corrosion, the fracture of these steels occurs also along the grain boundaries where due to carbide precipitation and different rate of diffusion of chromium and carbon in austenite the depletion of near-boundary regions by chromium takes place. Therefore, the ICF of welded joints of steels 304 and 316 in BWR pipelines at the US NPP was initially connected with ICC, because during metallographic examinations of pipeline metal the carbides of chromium $M_{23}C_6$ were revealed in the damage regions on the grain boundaries. However the rate of cracks growth in pipelines of these steels was at the level of 1–10 mm/year, which is not characteristic of ICF process.

According to the data of laboratory research the ICF depth in the sensitized steel should not exceed 50 μm after 20–30 years of pipeline service. It was concluded that operational damages of pipelines of stabilized (08Kh18N10T, 321, 347) and non-stabilized (304, 316) steels are connected with ICF process, not observed earlier, and developing in the presence of tensile stresses at the high rate after long-time incubation period.

Figures 3 and 4 present the autoclave test results of U-specimens, loaded by bending up to the stress of ~$R_{p_{0.2}}$, carried out to estimate the effect of the main «activators» of high-parameter water, i.e. oxygen and chlorine-ions, on the susceptibility manifestation of 08Kh18N10T steel to ICF. In pure water ($O_2 \leq 0.02$ % and $Cl^- \leq 1$ mg/kg) at the temperature 300 and 350 °C the cracking of specimens was not observed within 3000–3500 h of tests. The CC of specimens tested in media with increased concentration of oxygen or chlorine-ions started after the long-time incubation period which followed by the extremely high rate of cracks growth. At holding after incubation period within 250–500 h the tested specimens damaged with a crack initiation for the depth of more than 2/3 of thickness.

The adding more than 2 mg/kg O_2 to the water composition even at a low chlorine-ions content ($Cl^- \leq$ ≤ 1 mg/kg) causes CC of specimens after 2500–3000 h. Increasing Cl^- content up to 10 mg/kg CC is observed already after 1000 h. In all cases the cracks possess mainly intercrystalline nature and can be identified as cracks initiating at stress CC by ICF mechanism.

Thus, the violation of water-chemical condition, connected with increase in corrosion-active impurities content in the high-parameter water and their accumulation on the surface of pipes, made of chromium-nickel austenite steels, can provide conditions for realization of stress CC process.

Chromium-nickel steels with high resistance against corrosion cracking. The favorable effect on the chromium-nickel steels resistance against CC is attributed to the presence of δ-ferrite in their structure. The ultimate stresses, at which CC is not occurred yet, are increased already in the presence of 3–5 % of δ-ferrite. The increase of stability is noticeably observed at the δ-ferrite content of more than 20 %. Steels possessing a stable single-phase ferrite structure (08Kh17T, 15Kh25T, 15Kh28 and others) can serve as a reference of resistance against stress corrosion. At the tests in high-temperature water, containing 500 mg/kg Cl^- under conditions of alternate moistering and drying, the specimens of these steels are subjected only to pitting corrosion, but not to cracking.

The application of known ferrite steels with the conventional carbon and nitrogen content is hindered by their high susceptibility to brittle fracture. The chromium ferrite steels with a low content of mentioned impurities (to 0.015–0.020 % in total) are characterized by high ductility and impact toughness. Among them the steels EP 882-VI and EP 904-VI should be mentioned. They begin to find their application in power engineering machine building.

It is possible to provide the long service life of pipe systems applying chromium-nickel austenite-ferrite (duplex) steels consisting mainly of two phases, austenite and ferrite, for their manufacture. The quantity of each one is usually within the ranges of 40–60 %. The austenite-ferrite steels 08Kh22N6T (EP-53), 08Kh21N6M2T (EP-54), S32304 (03Kh23N4), S31803 (03Kh22N5M3), S32750 (03Kh25N7M4) and others are characterized by a high general corrosion resistance, not susceptible to stress CC, pitting and crevice corrosion in chlorine-containing media, have high values of tensile and yield strength at a satisfactory ductility and impact toughness, good weldability.

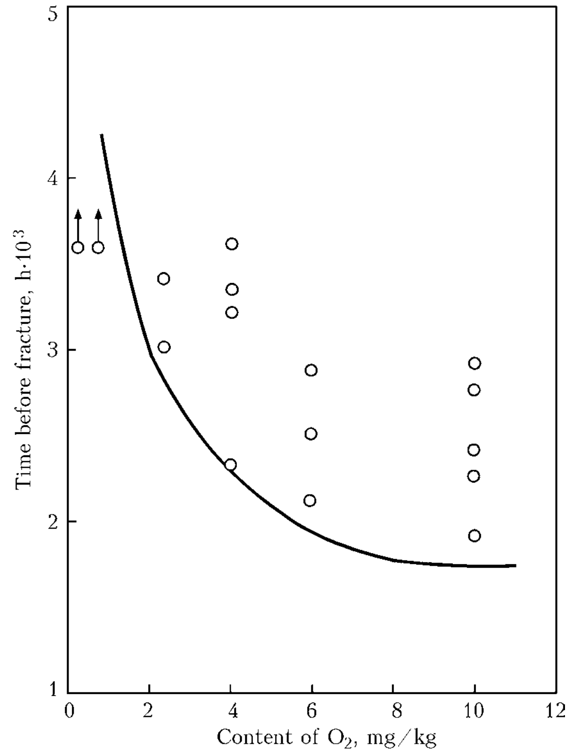

Figure 3. Effect of oxygen on time before fracture of U-specimens in water containing 1 mg/kg Cl^- at $T = 300$ °C, $\sigma \sim R_{p_{0.2}}$

Figure 5 presents the results of autoclave tests of U-specimens with the continuous loading in neutral chloride solutions, having exhibited a good correlation with the observed cases of corrosion behavior of specimens of austenite and austenite-ferrite steels. In the whole investigated range of Cl^- concentrations the austenite-ferrite steels 03Kh23N4, 03Kh22N5M3, 03Kh25N7M4 possessed indisputable advantages in resistance against stress CC, close to $R_{p_{0.2}}$, as compared

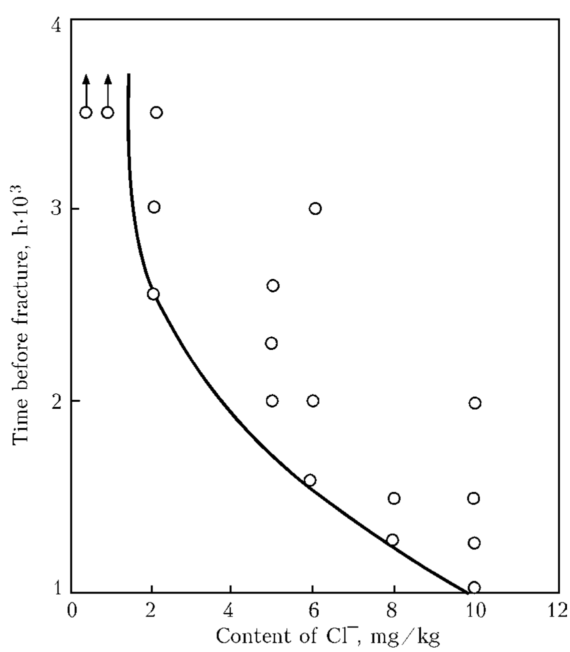

Figure 4. Effect of chlorine-ions on time before fracture of U-specimens in water containing 0.02 mg/kg O_2 at $T = 300$ °C, $\sigma \sim R_{p_{0.2}}$

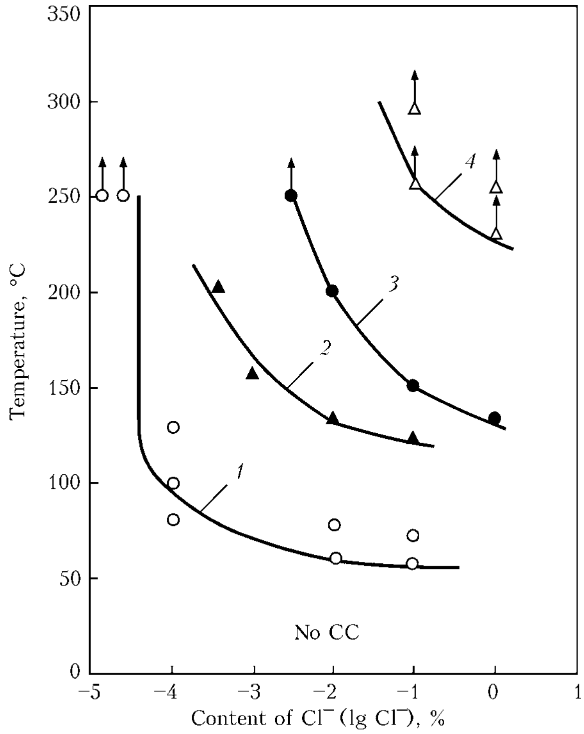

Figure 5. Effect of Cl^- content on susceptibility of steels to corrosion cracking: *1* — 08Kh18N10T, 304, 316; *2* — 03Kh23N4; *3* — 03Kh22N5M3; *4* — 03Kh25N7M4

with the steels 08Kh18N10T and 316. The advantages of austenite-ferrite steels are proved also by the results of tests in boiling water solution containing 40 % $CaCl_2$ (Figure 6).

The increase in nickel content in the chromium-nickel steels with the austenite structure improves their resistance against CC in high-temperature water. The minimum nickel concentrations, providing for the stability of steels against CC, depend on many factors: duration of products service, nature and degree of environment aggression, characteristics of stress-strain state and also content of the rest alloying elements in steels.

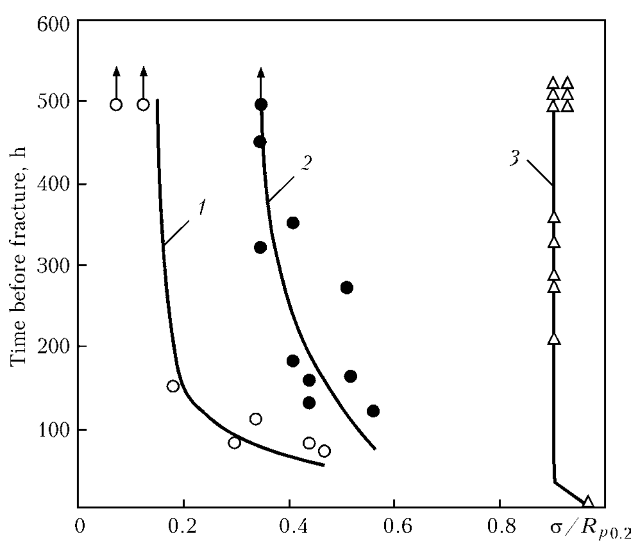

Figure 6. Effect of level of stresses $\sigma/R_{p_{0.2}}$ in U-specimens on resistance against cracking of steels in the boiling water solution containing 40 % $CaCl_2$: *1* — 08Kh18N10T, 321; *2* — 316; *3* — 03Kh22N5M3

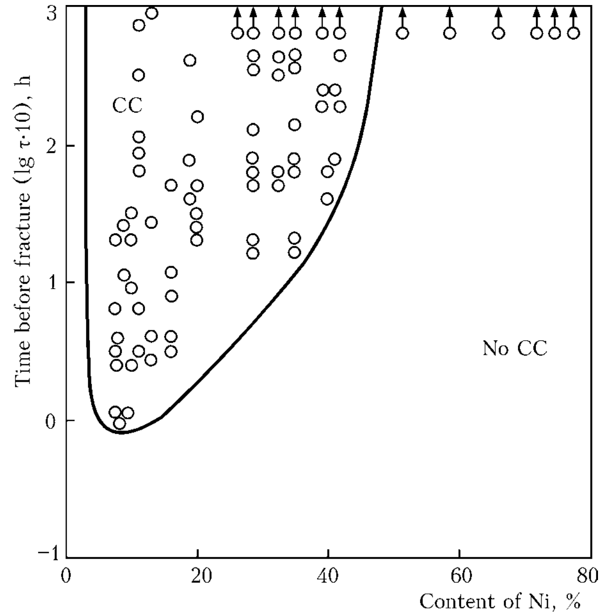

Figure 7. Effect of nickel content on susceptibility of stainless steels and alloys to corrosion cracking in boiling water solution containing 42 % $MgCl_2$

Figure 7 gives the results of investigations of nickel effect on the resistance of steels against CC in the boiling water solution containing 42 % $MgCl_2$. These results can be used for the prediction of corrosion resistance of definite steels in high-parameter water.

In the structures of steam generators of an increased reliability of reactor plants of the new generation it is necessary to provide the long life of piping systems, mainly, heat exchange pipes resistance against corrosion fractures. One of the possible ways to increase in steam generators life is the application of heat exchange pipe steels 03Kh21N32M3B (ChS-33), N08020 (02X20N35M3), N08825 (02X22N40M3), possessing much higher resistance against chloride CC under the operational conditions as compared with the steel 08Kh18N10T used nowadays.

The application of steel 03Kh21N32M3B (ChS-33) is challenging. In connection with the increased nickel content (≥ 32 %) the steel possesses considerably higher immunity against CC. The low concentration of carbon allows providing steel resistance against

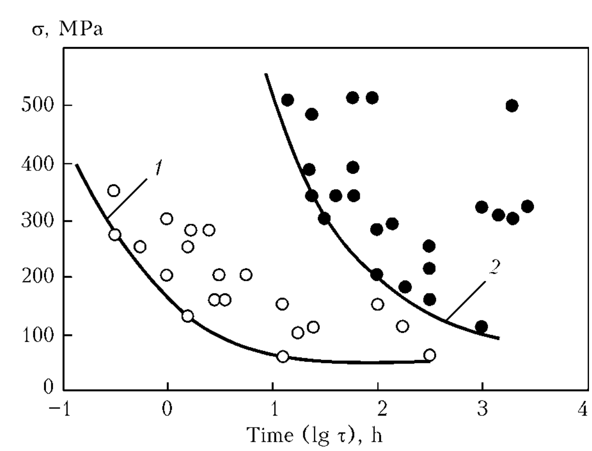

Figure 8. Resistance of steels against corrosion cracking in boiling water solution containing 42 % $MgCl_2$: *1* — 08Kh18N10T; *2* — 03Kh21N32M3B

ICC at niobium content 0.9–1.2 % within the wide temperature range of provoking heating, and the alloying by molybdenum provides the increased resistance against pitting corrosion. The steel 03Kh21N32M3B (ChS-33) and its foreign analogies are mastered in pipe industry, necessary for steam generators assortment.

The tests carried out in Central R&D Institute of Structural Materials «Prometej» (TsNIIKM) in boiling water solution, containing 42 % $MgCl_2$, prove the possibility of large increase in resistance against CC of heat exchange pipes of steam generators in use of steel 03Kh21N32M3B (ChS-33) for their manufacture (Figure 8). The fracture of specimens of this steel occurred at much higher loads during longer test period.

The tests of steel 06Kh20N35B (close by composition to 03Kh21N32M3B grade) were carried out at SPA Central R&D Institute for Heavy Engineering (TsNIITMASh) in high-parameter water at temperatures 320 and 350 °C with different oxygen and chlorine-ions content. These tests proved the considerable increase in resistance against CC during adding nickel into composition of steels in the amount of 30 % and more.

CONCLUSIONS

1. The service damages of pipelines and heat exchange pipes of chromium-nickel austenite steels 08Kh18N10T and foreign analogies, close to it, are caused by ICF process due to combined effect of corrosion properties of the medium, i.e. high-parameter water and stresses caused by operational pressure and technological loads in manufacture and erection.

2. The oxygen and chlorine-ions have a negative influence on the resistance of steels to CC in high-temperature water under conditions of high stresses, especially noticeable at 290 and 300 °C. ICF in high-parameter water is observed in chromium-nickel austenite steels, prone and resistant to ICC, that allows refer it to the special type of corrosion damage of metal.

3. The cracks initiating in the specimens during autoclave tests in high-parameter water with deviations in oxygen and chlorine-ions content are identical to service cracks in damaged pipelines and heat exchange pipes. They have a clearly expressed intercrystalline nature of developing, and the cracking process has a long time incubation period with a high next rate of crack growth.

4. To guarantee the long life of piping systems is possible using the following steels for their manufacture instead of chromium-nickel austenite steels 18-10, 17-13-3:

- austenite-ferrite (duplex) steels, the base structure of which consists of two phases — austenite and ferrite, characterized by high general corrosion resistance, not susceptible to stress CC, pitting or crevice corrosion in chlorine-containing environments;
- high-nickel austenite steels. The increase of nickel content in chromium-nickel steels with austenite structure increases their resistance against CC in high-temperature water. High-nickel steel 03Kh21N32M3B (ChS-33) is the challenging material for heat exchange pipes of steam generators of reactor plants of the new generation.

SCIENTIFIC-TECHNICAL PROBLEMS IN THE FIELD OF LIFE ASSURANCE OF BUILDING STRUCTURES

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The paper deals with the problems of development of normative-legal base for life assurance of constructions and development of methods for assessment of the life of structures, buildings and constructions taking into account the physico-mechanical properties of materials, technogenous and natural effects.

Keywords: *building structures, service conditions, deterioration, life specifying, operation, safety, technologies and materials*

Building sector of Ukraine is going through a period of intensive growth. A feature of its development at the current stage is solving a number of scientific-technical problems and development of normative documents, which cover the issues of specifying the life and safe operation of constructions, namely:

- pronounced deterioration of the existing constructions, the greater part of which have been in operation for 40 to 50 years and more;
- essential changes of service conditions of many buildings and constructions, caused by changes in their purpose, renovation, periodical replacement of process equipment, inner and outer networks;
- overall increase of the magnitude of loads and impacts which affect building structures in operation of buildings and constructions;
- introduction of new technologies and structural materials (in particular, expansion of monolithic-skeleton construction, new kinds of reinforcing bars, concretes and additives to them, new systems of structure enclosures, etc.);
- an acute need for intensive building of social housing);
- development of new kinds of constructions: high-rise buildings, multistoreyed underground structures, large-sized transportation structures;
- mastering territories unsuitable for construction (landslide slopes above mining excavation sites, underflooded territories, river and sea shores, etc.)
- erection of multistoreyed and large-sized houses, above-ground and underground structures in dense city coverage.

By the initiative of B.E.Paton, President of the National Academy of Sciences of Ukraine [1], the concept of life is now also applied in construction.

Life of an engineering construction is understood to be its total service life (counted in years for a building structure) from the beginning of operation or renovation after repair up to reaching the limit stage [2]. Construction life at transition to the limit stage, in other words residual life, is determined by the results of monitoring the technical state of a construction. The limit stage of a construction is understood to be such a state beyond which normal operation of a construction is not ensured. Normal operation of a construction is a totality of situations, in which the construction is running, respectively, in keeping with the operation technology accepted in the project, including operation at specified power levels, processes of equipment starting and stopping, maintenance and repair.

For building structures a distinction is made between two groups of limit stages: first — by power and resistance; second — by deformation limitation. Maintaining the life of constructions consists in implementation of such operation methods, which ensure the strength, resistance and limitation of deformations of structures with a certain level of reliability to guarantee normal operation of a construction.

Life exhaustion for most engineering constructions consists, mainly, in certain differences compared to moving engineering objects. These differences, which should be taken into account in normative-legal provisions for construction, are determined by the following features:

- buildings and constructions are built on soils in different engineering-geological conditions, which may change in time, and essentially influence structure behaviour and construction operation;
- currently observed worldwide tendency of increasing of the magnitudes of natural climatic and seismic impacts on constructions, which should be reflected in building specifications, and this means that parts of the current constructions do not have a sufficient level of reliability and safety and have to be reinforced;
- constructions are built for long-term operation (100 and more years), and architectural monuments have been standing for centuries and during this entire time their life has to be maintained;
- with considerable life spans of constructions as a whole their individual elements have a relatively shorter term of efficient operation. For instance, facade systems and roofing have several times shorter term of reliable operation compared to the main load-carrying structures, and, therefore, need periodical repair and replacement, this essentially influencing the functioning of the main long-term operation elements;

• technical state and life of current constructions are essentially (usually, negatively) affected by new construction and infrastructure, which is built nearby.

The building normative documents and normative-legal acts usually consider the issue of construction life indirectly. New normative-legal documents have been recently developed, which directly cover the life of structures and constructions as a whole. So, «Technical Regulations for building products, buildings and constructions» [3] approved by an Act #1764 of the Cabinet of Ministers of Ukraine of 20.12.2006, state the following: «Constructions as a whole and their individual parts should be fit for purpose and meet the main requirements made of them. Under the condition of appropriate operation of constructions, the main requirements to them should be met during the design service life of constructions allowing for unforeseen impacts».

In 2007 GSN V.1.2.-2:2006 «Loads and impacts. Design norms» were introduced [4], which for the first time in construction norms allowed for the influence of building and construction operating terms on the strength of impact on them, depending on the degree of their criticality. Thus, dependence of the required load-carrying capacity of a structure, and, therefore, of structure life on the design life of constructions is specified for the first time.

GSN V.1.2-5:2007 «System of provision of reliability and safety of constructions. Scientific-technical supervision of constructions» [5] were introduced starting from 01.01.2008. This document systematizes for the first time various research performed at design and operation of constructions, places it into a normative framework, which will allow accumulating the necessary statistical material through purpose-oriented full-scale research, in order to perform analysis and development of optimum methods for specifying and ensuring the life of buildings and constructions.

State Research Institute of Building Structures (NIISK) together with leading scientific organizations of the construction industry and the S.I. Subbotin Institute of Geophysics prepared GSN V.1.1-12:2006 «Construction in seismic regions of Ukraine» [6], which were introduced from 01.02.2007. These norms give detailed definitions of the parameters of seismic impacts on constructions in different regions of Ukraine, refined methods of calculation of structure stressed state for seismic impacts, introduce a new classification of buildings by their resistance to seismic impact.

NIISK participated in development of the State Scientific-Technical Program «Resource» initiated by the National Academy of Sciences of Ukraine, and in substantiation of the State Program of ensuring technological safety in the main sectors of economy (in terms of building sector problems).

In order to develop these programs NIISK is conducting investigations for extension of the life of particularly important and potentially hazardous constructions. As an example, we can mention the currently performed package of work on evaluation of the technical state and re-assessment of the specified life of production facilities and constructions of the first and second power unit of Rovny nuclear power plant, which include systems which are very important in terms of safety. Design operating life of RNPP power units will be over in several years, and without timely substantiation of the possibilities of its extension (and necessary repair and reinforcement of structures) further reliable operation of these facilities will become impossible.

General view of reinforcement structures of «Ukrytie» western fragment

NIISK has worked for many years to solve the construction problems of «Ukrytie» Construction of the Chernobyl NPP for its reshaping into an ecologically safe system and construction of a new safe confinement [7]. Work on stabilization of «Ukrytie» structures has now been completed, including the most complex work on enhancement of its western fragment (Figure).

This work is performed together with the Kiev «Energoproekt» Institute, as well as scientific organizations of the NAS of Ukraine: STC «Ukrytie» (now Institute for Problems of Nuclear Power Plants Safety), the S.I. Subbotin IGPh, and the E.O. Paton Electric Welding Institute.

Residual life of «Ukrytie» building structures was determined proceeding from full-scale investigations, many years of observation and generalization of the technical condition, as well as the nature of interaction of «Ukrytie» tumbledown and new structures, retrospective analysis of the probability of development of maximum loads, as well a seismic influence of snow, wind, temperature variations, and tornadoes. Probabilistic term of further safe operation of «Ukrytie» equal to approximately 15 years was also established and substantiated. The immediate task is that of construction of a new safe confinement with guaranteed service life of more than 100 years.

Over the recent years NIISK performed scientific work on renovation and extension of the life of major architectural monuments such as Odessa Opera House [8], St. Sofia Cathedral, Pecherskaya Lavra, Cultural Arsenal in Kiev, etc. These operations are of a complex nature, and include external examination of structures, establishing the features of interaction of their structural elements, construction of 3D structural models of these constructions, determination of strength parameters of materials and elements, as well as load-carrying capacity as a whole, performing development in keeping with the requirements of current building specifications.

These works contain a considerable scope of information-analytical materials for solving the problem of exhaustion of the life of the existing stock of concrete and stone structures, which require generalization and dissemination in the broad circle of building sector specialists.

Thus, over the recent years, a considerable scope of research work has been performed, a number of normative documents have been prepared, which addressed the problems of evaluation and improvement of the life of building structures. However, system approach to solution of these problems, which would allow an integrated solution of the issues of evaluation of the reliability and fatigue life and residual life of building structures, is lacking so far.

Expediting the solution of problems of improvement of life and operational safety of construction structures requires focusing the activity of research organizations of building industry with participation of the NAS of Ukraine and Ministry of Education and Science of Ukraine to solve such urgent scientific and technical problems as:

• determination of the regularities of variation of the characteristics of strength and reliability of structural systems of buildings and constructions in time under the impact of the set of loads and actions on them, substantiation of physical methods of evaluation of the fatigue life of constructions;

• substantiation of global changes in the structure and magnitudes of the natural and antropogenic components, affecting the constructions, which are currently occurring, and forecasting such changes for the long-term period in comparison with the life spans of such objects (at least for 50–100 years);

• more profound investigations of the interaction of complex structural systems in constructions, influence of individual elements on the performance of systems as a whole, interaction of complex construction systems with the environment (mainly, with the soil bases);

• more profound investigations of the interaction of neighbouring constructions with each other, studying the influence of new constructions on the surrounding buildings, which is particularly important under the conditions of more and more congested urbanized environment;

• solving the ecological issues, which accompany the constructions at all stages of their life (influence of buildings and constructions on the environment during construction and operation, reclaiming and recycling of building materials and structures after demolition of the constructions, etc.).

The main problems faced by the building sector and related to the problem of extension of the life of constructions, include:

improvement of the national normative base in the building sphere. In addition to improvement of the normative documents currently in force, the top priority measures include development of State Building Specifications for diagnostics of the technical state of structures of buildings and constructions and Norms on examination of the technical state and certification of residential and public buildings;

ensuring protection of territories, other buildings and constructions from the adverse influence of natural and technogenous factors. Priority measures include development of normative and procedural documents, concerning extension of the life of constructions in regions of higher seismic risk, which were constructed earlier without consideration of any measures to provide the seismic resistance;

expansion of experimental design and construction with mandatory scientific support and construction of buildings by well-established projects for mass application. An urgent task is wider application of design solutions of buildings with high technical and economic characteristics for different regions of Ukraine, which will provide a faster solution of the problem of construction of social housing;

enhancement of the influence of science on solution of the issues of quality control, investment project review, and certification of building sector products. Ukraine's entering WTO, in addition to measures on protection of the local market from low-quality products, requires an essential increase of the competitiveness of manufacturing building materials and products and building of constructions as a whole by Ukrainian builders;

improvement of the methods of scientific support of potentially hazardous and particularly critical constructions in all the stages of their life. Scientific support is highly urgent both for constructions built over the previous years (architectural monuments, HPP, NPP, TPP constructions, etc.), and for those which are currently being built (safe confinement over the «Ukrytie» of Chernobyl NPP, high-capacity public facilities).

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WELDING AND CLADDING OF HEAT-RESISTANT NICKEL ALLOYS WITH SINGLE-CRYSTAL STRUCTURE

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Weldability criteria for heat-resistant single-crystal nickel alloys have been determined. The mechanism has been studied, and causes of cracking have been established, which include deviations of crystallographic orientation of the weld metal from the initial one, and formation of stray grains. The effect of welding parameters and conditions, as well as of crystallographic orientation of welded joints, on the above characteristics has been investigated. Conditions of formation of crack-free welds at minimal mismatching of crystallography and structure of the base and weld metals have been identified.

Keywords: *heat-resistant nickel alloys, single crystals, welding, cladding, crack resistance, crystallographic orientation, shape of solidification macrofront, thermal gradient, stray grains, solidification direction, temperature gradient, local stress zones*

Improvement of performance of aircraft and marine gas turbine engines, as well as stationary gas turbine plants can be achieved by continuously increasing temperature of a working medium, i.e. gases at the turbine inlet. In turn, this leads to the need for application of super heat-resistant materials. Such materials include multiple-component directional solidification nickel-base alloys. Working characteristics of the alloys can be substantially improved if they are used in the favourable, structurally oriented or single-crystal state.

Complex alloying and structure of single-crystal heat-resistant nickel alloys, and absence of high-angle grain boundaries — these are the factors that provide a set of required mechanical properties and maximal service life of products, on the one hand, and deteriorate their weldability because of high sensitivity to cracking, on the other hand. The problem of providing sound welded joints on heat-resistant single-crystal nickel alloys cannot be solved without investigation of the mechanism and peculiarities of formation of a structural state, as well as crystallographic features of the weld metal. High strength of the alloys at increased temperatures, low thermal conductivity, wide brittle temperature range, and low safety factor for deformability within this range lead to considerable welding stresses and low relaxation ability, which promotes cracking of the welds during the welding process. Therefore, sensitivity to cracking during welding must be taken as the main qualitative indicator of weldability of the said materials. Not less important is the degree of structural and crystallographic degradation of the initial single crystal, which is evaluated by the following factors:

- change of crystallographic orientation of the weld compared with the initial (base) metal;
- presence of grains in the weld with other orientation than that of the base metal grains;
- changes in dislocation structure of the weld and HAZ.

As known from practice of growing of single crystals [1—4], the optimal values of indicators of perfection of an alloy can be achieved under certain temperature-time and orientation conditions expressed in terms of the values and direction of maximal thermal gradient $\overline{G}$ at the solidification front, solidification rate R, their ratio, and crystallographic orientation of a seed used to grow crystals. However, the values of these parameters, as well as their implementation processes indicated to create equilibrium conditions for production of single crystals, cannot be used for the welding processes because of the temperature-force and spatial peculiarities of fusion welding, other than the metallurgical ones.

In this connection, theoretical background and quantitative characteristics of the process parameters, which provide formation of single-crystal structure in growing of single crystals, can be used only as premises in description of formation of structure of the welded joints.

There are only few publications [5—8] on welding nickel single crystals, and they consider only individual aspects of the above problem without finding a comprehensive system solution to it. Moreover, they consider particular aspects without technological recommendations.

The purpose of this study was to carry out a series of investigations to establish peculiarities of structural and crystallographic changes in electron beam welding (EBW) and cladding of heat-resistant single-crystal nickel alloys, as well as the impact on them by the technological factors.

Parameters and conditions (preheating, cooling) of welding were determined to be the main technological means of affecting the temperature-time conditions of formation of structure of a welded joint.

Experimental procedures. Typical high heat-resistant alloy JS-26, widely applied for manufacture of gas turbine blades, which contains more than 50 % of the strengthening γ'-phase in the single-crystal state and is considered to be almost unweldable, was chosen as a material to be investigated. Chemical composition of the alloy is as follows, wt.%: 0.13–0.18 C, 4.3–5.6 Cr, 8–10 Co, 0.8–1.4 Mo, 10.9–12.5 W, 1.4–1.8 Nb, 5.5–6.2 Al, 0.8–1.2 V, 0.8–1.2 Ti, 0.015 B, 0.025 Ce, 0.005 Y, 0.005 La, 0.015 P, 0.25 Mn, 1.0 Fe, Ni — base.

Specimens for welding experiments, measuring 50 × 50 × 2–3 mm, were cut out from flat 5–8 mm thick single-crystal billets grown by the high-rate directional solidification method. Because the overwhelming majority of repair operations on blades are performed by cladding onto an end surface, part of the investigations was carried out on claddings on the end surfaces of the said billets.

Orientation of the specimens was chosen from a wide range of crystallographic directions: from those coinciding with high-symmetry axes of the fcc crystal to those equidistant from them (centre of the stereographic triangle).

Welding was performed both with preheating of the weld edges to a temperature of 200–600 °C and without it. The welding speed was varied within the technologically acceptable ranges (from 5 to 80 m/h). Specific values of the welding parameters were chosen on the basis of requirement for formation of welds with a certain penetration depth, geometry and quality. Preheating was carried out in order to create more equilibrium temperature conditions for formation of the weld and single-crystal structure.

Cladding onto the end surfaces was performed by the layer-by-layer electron beam method using filler material of the same composition as that of the base alloy. Thickness of the layer deposited per pass was 1.5–2.0 mm.

Sensitivity to cracking during welding was evaluated on the basis of the quantity of cracks in welds of the circular patch test considered in studies [9–12] and optimised for the used thicknesses. Circular welds 3–5 mm wide, depending upon the welding speed, were made on a diameter of 40 mm. To compare, investigations were also conducted on the straight-line welds and claddings.

Metallographic examinations using the «Neophot-30» microscope were carried out on surfaces and ends of the sections made by the standard procedure, with subsequent chemical and vacuum etching and oxidation. X-ray examinations were performed on the same sections using the following procedures.

Crystallographic orientation of the specimens was determined by pole figures {220} and {111} using the back-reflection technique. Distribution of the intensity of scattered X-ray radiation near the reciprocal lattice points was studied by the orientation X-ray method [13–18]. Standard diffractormeter DRON-3M with monochromated Cu_{K_α} radiation and special specimen holder was used with this method, thus providing a four-circle equatorial geometry of an experiment and X-ray reflections without a specially oriented preparation of single-crystal specimens. Distributions of the intensity along diffraction vector, $\mathbf{G}(\mathbf{q} = \mathbf{G}/|G|)(\mathbf{I}_{\mathbf{q}\|})$, and in a plane normal to it, $\mathbf{I}_{\mathbf{q}\perp}$, were analysed. Intensity distributions $\mathbf{I}_{\mathbf{q}\|}$ (or θ–2θ X-ray patterns) were used for phase analysis and evaluation of residual stresses. Shape, half-width $\delta_{\mathbf{q}\|}$ and position of maximum of distribution $\mathbf{I}_{\mathbf{q}\|}$ were determined from the physical profile of experimental lines plotted with allowance for the reference specimen using Fourier transformation. Distributions $\mathbf{I}_{\mathbf{q}\perp}$, their shape and half-width $\delta_{\mathbf{q}\perp}$ were used to investigate sub-structure of single crystals. According to the theory of X-ray scattering by non-ideal crystals [16], $\mathbf{I}_{\mathbf{q}\perp}$ and $\delta_{\mathbf{q}\perp}$ are determined by density, type, location and uniformity of distribution of dislocations in a material. Distributions $\mathbf{I}_{\mathbf{q}\perp}$ and $\mathbf{I}_{\mathbf{q}\|}$ were studied from reflections {220}, {110} and {331}. At the same time, the area of the irradiated surface changed from 0.1 to 2.0 mm^2, depending upon the character of an experiment, which made it possible to evaluate the experimental data at a mesoscopic structural level.

Results and discussions. *Sensitivity to cracking*. Transverse cracks in the weld metal, having an intermittent character, are characteristic defects in EBW of heat-resistant nickel alloys containing more than 50 % of the γ'-phase (alloy JS-26 belongs to this group of the alloys) (Figure 1). Usually, these cracks cross the weld and «attenuate» either at the fusion line or in HAZ.

Temperature-time parameters of formation of a welded joint, which depend upon the welding speed, preheating and heat removal, are the key factors determining the probability of cracking. Transverse cracks take place mainly in the presence of high temperature gradients and cooling rates, high welding speed and specific power, and enhanced heat removal, where substantial stresses and strain rates are formed in a welded joint. The crack-free joints can be provided within a narrow range of welding parameters and conditions. For metal 1–3 mm thick, the cracks are formed at a welding speed of over 15 m/h. Preheating of the weld edges to 350–450 °C allows increasing the welding speed to 25 m/h, whereas enhanced cooling (by using massive assembly-welding fixture and heat-intensive units), on the contrary, draws it close to 5 m/h.

Investigation of topography (see Figure 1) and fractography (Figure 2) of the crack surfaces, and direct examination of initiation of the cracks during welding suggest that most probably they are of the type of the low-temperature ductility-dip (*DTR*) cracks [17].

It should be noted that the sensitivity to cracking was much lower in making end claddings. For example, whereas the butt welds 60 mm long and 12 mm^2 in cross section, made at a welding speed of 40 m/h and metal thickness of 2 mm, contained 7–8 cracks,

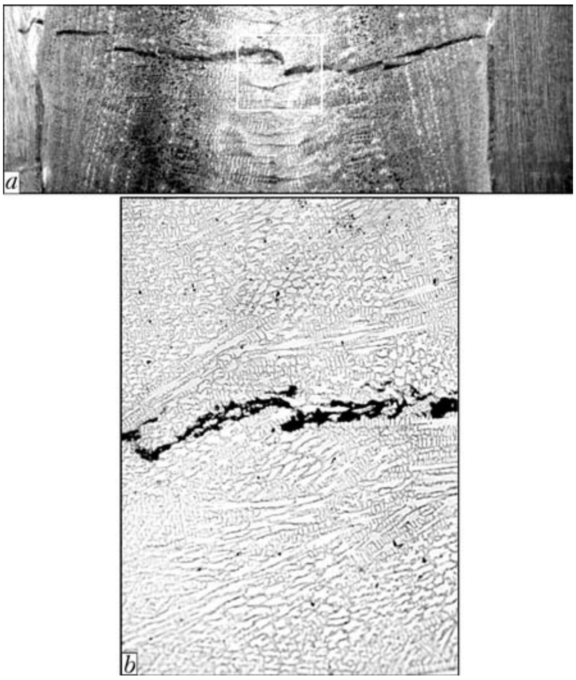


Figure 1. Cracks in weld metal: *a* — surface of welded joint (×25); *b* — microsection (×200)

the claddings of a large cross section and length contained only 1–2 cracks. And in a number of cases (at low heat input and welding speed) no cracks were detected.

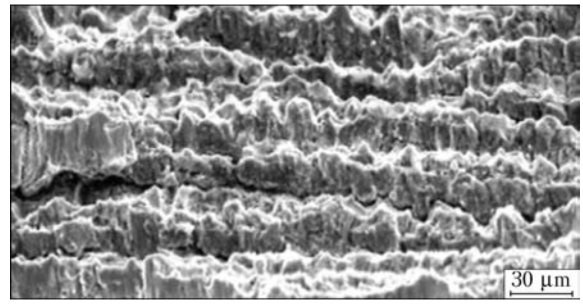


Figure 2. Fractography of crack surface

Degree of structural and crystallographic degradation of initial single crystal. The weld metal inherited crystallographic and structural orientation of the initial single crystal in almost all the cases of the considered crystallographic orientations of specimens close to (001), (110) and (111) at a specimen thickness of 1.5–3.0 mm, welding speed of 5–80 m/h and preheating temperature of 200–600 °C (Figures 3 and 4). However, the degree of inheritance, i.e. angles of deviation from the initial orientation, presence of stray grains in the weld structure, and density and distribution of dislocations, had its own specific features in each particular case. The key technological factors for a given initial single crystal, which determine these specific features, are the welding parameters and conditions.

Good inheritance of the initial crystallographic orientation is achieved at a welding direction close (within 5°) to <100> and fusion surface (100) (Fi-

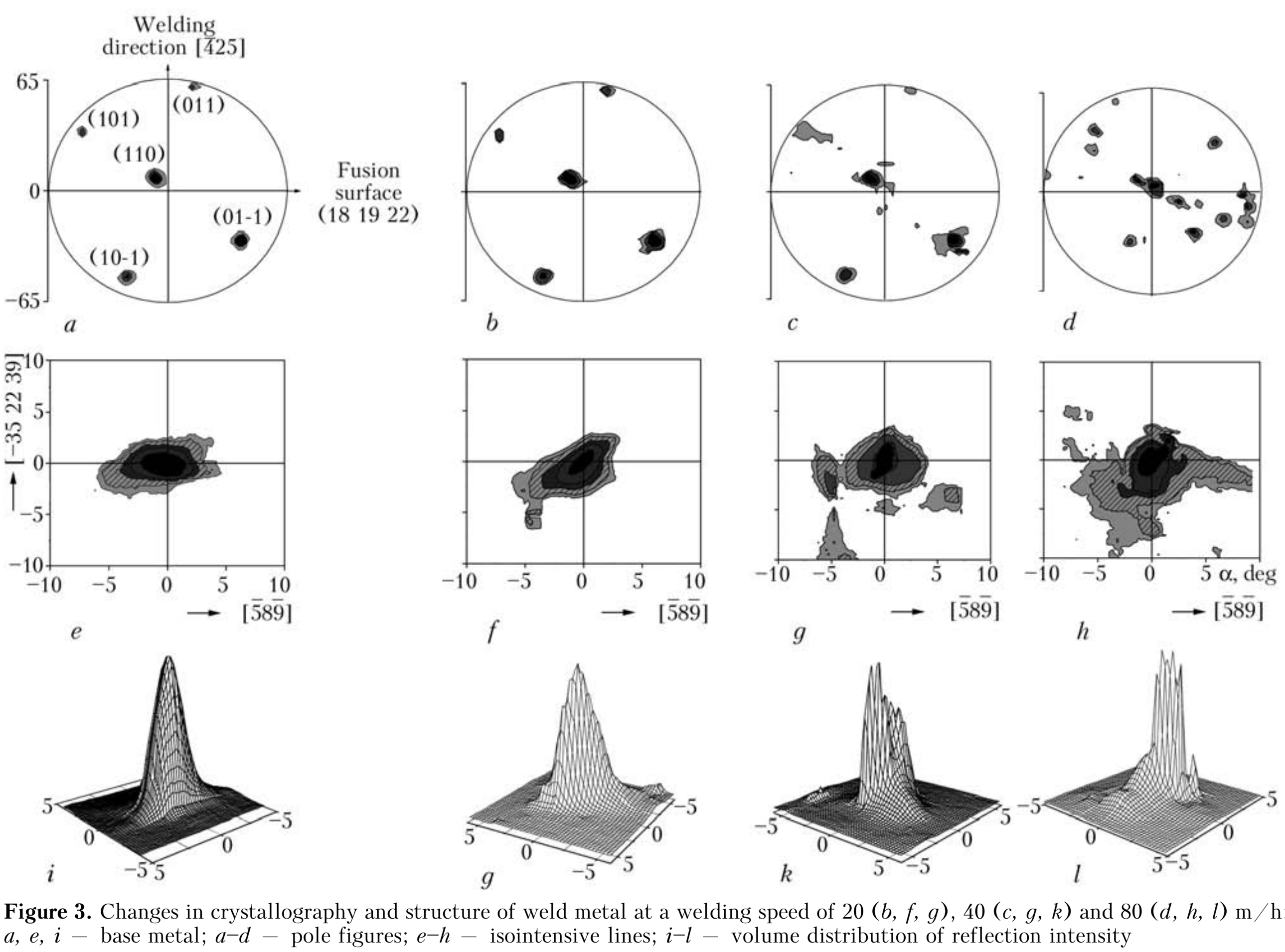


Figure 3. Changes in crystallography and structure of weld metal at a welding speed of 20 (*b, f, g*), 40 (*c, g, k*) and 80 (*d, h, l*) m/h: *a, e, i* — base metal; *a–d* — pole figures; *e–h* — isointensive lines; *i–l* — volume distribution of reflection intensity

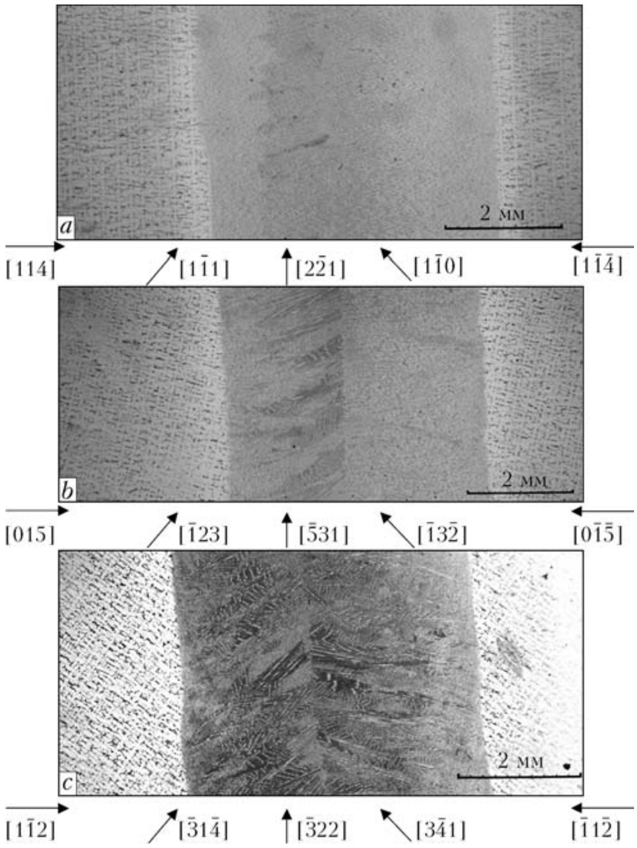


Figure 4. Changes in structure and crystallographic characteristics depending upon the angle between the welding direction and orientation of preferential growth of single crystal for welded joints made at a welding speed of 20 m/h: *a* — specimen surface orientation close to (001); *b* — close to (34$\bar{2}$), *c* — close to (671)

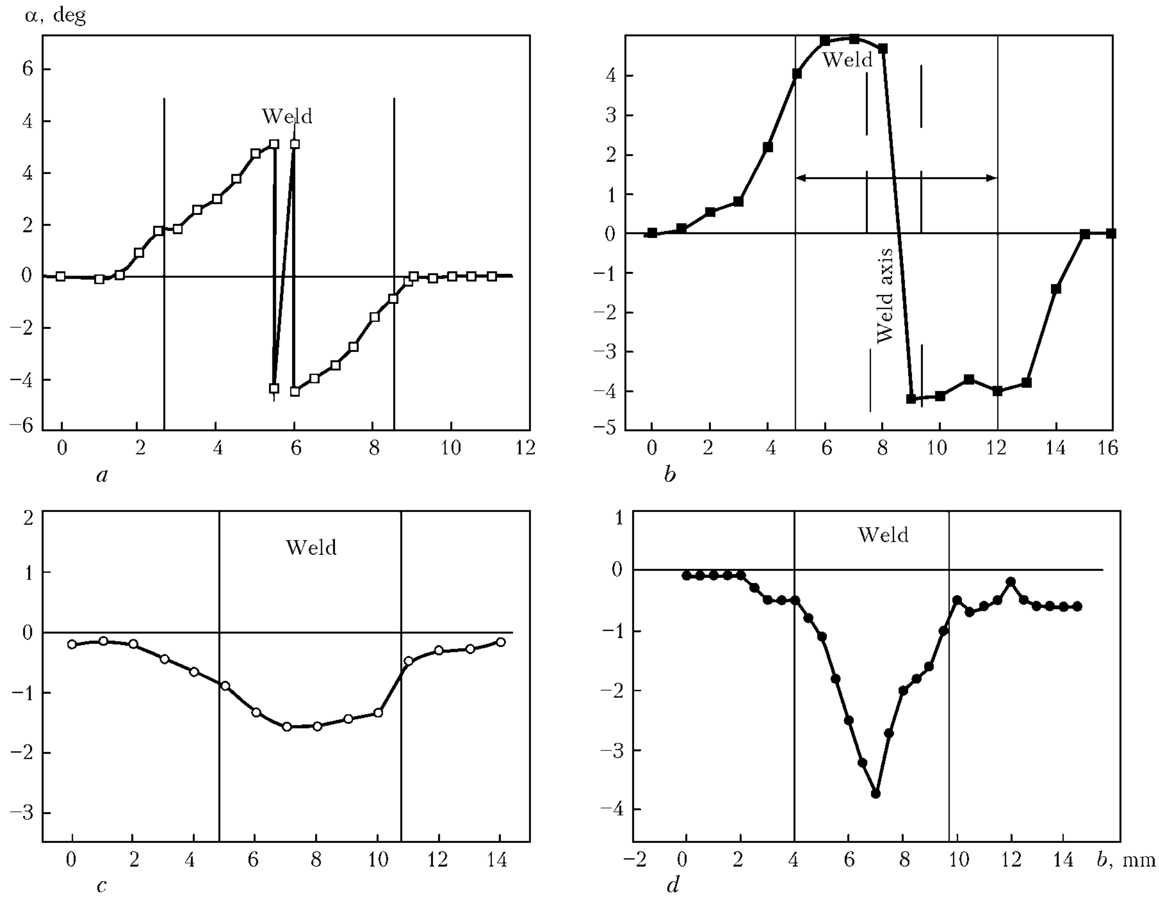
gures 4 and 5). However, even by meeting this requirement, because of a complex geometry of the solidification front of the weld pool, direction of a minimal thermal gradient on its perimeter does not always coincide with direction of the preferential growth of the initial single crystal. This situation leads to deviation of the orientation of metal with distance to the weld axis from the initial one (see Figure 5), and to formation of stray grains (see Figure 4). Moreover, a change in orientation (turn) occurs towards the nearest direction <100> on the side of each fusion surface. The more the initial orientation or welding direction differs from the high symmetry direction, the more pronounced is the deviation of orientation of the weld metal from the initial one, which is accompanied by formation of a large number of stray grains. At a substantial crystallographic asymmetry of the weld pool, the deviation of orientation may change the sign, while passing through the weld axis, and reach ±6°. The formation of grains also depends upon where the welding is directed to from the nearest high-symmetry direction. The quantity of grains is determined by the value of this deviation (see Figure 4).

Causes of formation of stray grains. The first cause is a loss of stability of solidification at its front because of the high orientation sensitivity of growth of dendrites in the presence of chemical and thermal gradients at the inter-phase surface, as well as violation of thermal and orientation conditions of directional solidification. These processes are well described in studies [4–8, 18, 19].

The second cause is heterogeneous stress fields with different dislocation structures, which are induced in the weld metal during the process of formation of welding stresses in cooling of the solidified weld metal. At this point we have to emphasise the role of shear stresses in slip planes, allowing for their values and distribution. According to the Schmid law, they are determined by the initial angle between the elongation axis, slip plane and direction, and, as applied to the welded joints, by the angle between the nearest high-symmetry axis of a single crystal [20] and direction of a maximal temperature gradient along the solidification front of the weld pool of a variable curvature. As a result, different regions of the weld are characterised either by different local stresses (large number of slip systems with low shear stresses), or by different dislocation density (small number of slip systems with maximal stresses). The values of these stresses and their distribution across the welded joint depend upon the crystallographic direction of welding. An increased dislocation density with subsequent fragmenting of a crystal and formation of grain boundaries take place in regions of the weld where shear stresses in slip planes are higher (high values of the Schmid factor). These grains can be classified as the strain ones.

The impact by crystallographic asymmetry of a welded joint becomes particularly pronounced when direction of a maximal thermal gradient, which varies along the weld pool solidification front, passes through direction <111>.

Along with crystallographic orientation of the initial metal, a marked effect on formation of structure and crystallography of the weld metal is exerted by welding parameters and conditions. This effect shows up as changes in the weld pool shape and temperature-time conditions of formation of structure of the weld metal. The shape of the weld pool solidification macrofront at a high welding speed of 60–80 m/h promotes a more complete inheritance of crystallographic orientation of the fusion surface. However, this leads to a substantial increase in the temperature gradient, as well as level and rate of growth of welding stresses, and to a reduction in time during which the weld metal dwells at high temperatures. The total dislocation density in the weld metal grows 15 to 50 times [20]. Incomplete relaxation of stresses and homogenisation of structure take place. This involves anisotropic distribution of dislocations and formation of zones of local stresses in heterogeneous dislocation ensembles, which for a metal of low ductility in the sub-solidus zone may be accompanied by further decrease in perfection of the single-crystal structure and appearance of regions with high-angle disorientation (see Figure 3). Development of heterogeneous disorientations usually leads to acceleration of deformation and fracture of a material. At a low welding speed



	Specimen surface	Welding direction	Fusion surface	Presence of grains
a	(213)	$[\bar{6}\ \bar{3}5]$	$(\bar{1}20)$	Over entire weld
b	(416)	$[6\ \bar{5}\ \bar{3}]$	$(612\ \bar{5})$	On one side
c	$(\bar{1}\ \bar{1}7)$	[611]	$(8\ \bar{4}\bar{3}5)$	Individual
d	(213)	$[\bar{1}02]$	$(6\ \bar{5}3)$	Same

Figure 5. Deviation of orientation across a welded joint from the initial one depending upon the crystallography of welding: *b* — specimen width; α — angle between the fusion line and plane of the (313) (*a, c, d*) and (220) (*b*) types closest to the welding direction

(10–20 m/h) and preheating, despite a lower solidification rate and deterioration of conditions of precise inheritance of crystallographic orientation of the initial material, caused by the shape of the weld pool solidification front, increase in time of dwelling of the weld metal at high temperatures promotes formation of more homogeneous dislocation ensembles (see Figure 3). The dislocation density in this case increases more than by an order of magnitude. The uniform distribution of dislocations causes formation of a subgrain structure with low disorientation angles.

It can be concluded from the above investigations that the main cause of transverse cracking is formation of local regions of increased stresses related to a non-uniform distribution of dislocations, caused by the said crystallographic asymmetry of a welded joint, as well as «low-temperature» mechanism of structure formation, rather than violation of single-crystallinity of the weld metal or changes in the γ- and γ′-phase mismatching parameter, which is not in excess of 0.01 % within the limits of the error of measuring a shift of maxima of X-ray reflections $\mathbf{I}_{q\|}$. The above low-temperature mechanism takes place at high welding speeds, substantial specific power of a heat source and intensive heat removal.

The loss of single-crystallinity is affected by the state of metal before welding, in addition to the initial crystallographic orientation. Stringent requirements for the initial structural state are imposed on nickel superalloys brought by complex alloying to the ultimate values of strength characteristics. Increasing the dislocation density by an order of magnitude may lead to formation of high-angle grain boundaries, local excessive stresses and, as a result, to cracking.

Structural distortions in the welded joints, particularly in the fusion zone and at the weld axis, can be diminished by limiting the content of interstitial impurities, and especially their non-uniform distribution in the initial material and filler. Therefore, the single-crystal metal prior to welding should be sub-

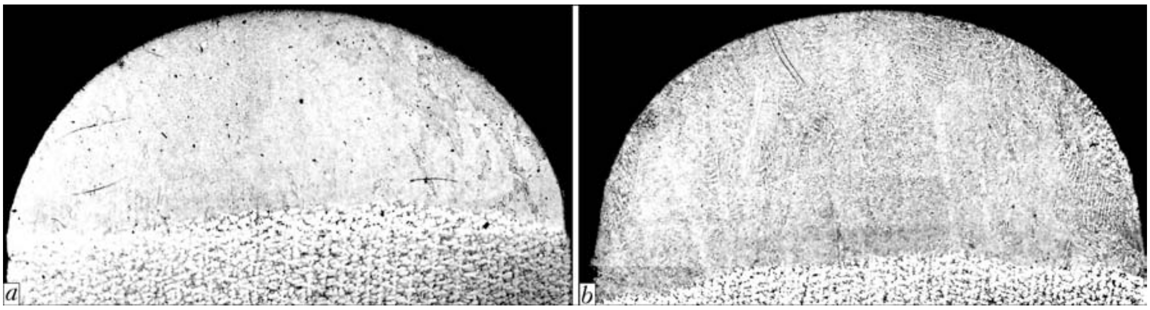


Figure 6. Macrosections of two-pass (*a*) and three-pass (*b*) cladding onto a plate end, cladding direction [013], cladding plane (100), and section plane (031) (×15)

jected to heat treatment to relieve cold working and residual stresses, and homogenise structure and chemical composition. Moreover, welding parameters and conditions should be stringently regulated.

It should be noted that the effect of technological factors on deviation of crystalline orientation of the weld metal from the initial one, formation of stray grains, and density and distribution of dislocations established for the welds take place also in cladding onto the end surfaces of single-crystal specimens. However, it is much lower mostly because of a smaller curvature of the macrofront of solidification of the cladding metal, which may be plane or even convex in some cases (Figure 6), in contrast to the welds where it is always concave. Whereas the deviation of orientation for the welds may amount to 6°, and quantity of stray grains may be 50 %, the deviation of orientation for the claddings is not in excess of 2°, and only isolated stray grains are formed.

CONCLUSIONS

1. Weldability of single crystals of heat-resistant nickel alloys is evaluated by their sensitivity to cracking, degree of deviation of crystallographic orientation of the weld metal from the initial one, presence of stray grains in the weld, and density and distribution of dislocations.

2. Sensitivity to cracking is determined mostly by the welding speed, specific power of a heat source, and presence of preheating of the weld edges.

3. Degree of deviation of crystallographic orientation of the weld metal from the initial one, and presence of stray grains in the weld metal depend mainly upon the crystallographic orientation of the initial single crystal and welding direction, as well as upon the geometry of the weld pool solidification macrofront.

4. It is necessary to do the following to provide crack-free welds on single crystals of heat-resistant nickel alloys of the JS-26 type with a minimal distortion of the initial crystallography and microstructure:

• to subject specimens before welding to heat treatment in order to relieve cold working and residual stresses, and to homogenise micro- and dislocation structure and chemical composition at the absence of high-angle grain boundaries;

• to ensure minimal deviation of crystallographic orientation of a single crystal and welding direction from the direction of high-symmetry axes;

• and to perform welding at low (about 10–15 m/h) speeds with preheating of the weld edges to 600 °C.

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