E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine

International Scientific-Technical and Production Journal

The Paton WELDING JOURNAL

October–November 2013
Nos. 10–11
Published since 2000

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

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

Publisher
International Association «Welding»

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State Registration Certificate
KV 4790 of 09.01.2001
ISSN 0957-798X

Subscriptions
$348, 12 issues per year,
air postage and packaging included.
Back issues available.

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Plenary Papers of the International Conference
«Welding and Related Technologies. Present and Future»
25–26 November, 2013, Kiev, Ukraine

95th BIRTHDAY ANNIVERSARY OF THE NATIONAL ACADEMY OF SCIENCES OF UKRAINE AND PATON BORIS EVGENIEVICH, ITS PRESIDENT

Boris Evgenievich Paton is an outstanding Ukrainian scientist in the field of welding, metallurgy and technology of materials and materials science, prominent public figure and talented organizer of science, academician of the National Academy of Sciences of Ukraine, Academy of Sciences of the former USSR and Russian Academy of Sciences, professor, honoured personality of science and technology of the Ukrainian SSR, laureate of the Lenin Prize and State Prizes of the USSR and Ukraine, 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.

Boris Paton, together with his father Evgeny Oscarovich Paton, established a world-known Paton's scientific school.

The international authority of B.E. Paton is a result of his extensive and extraordinary fruitful scientific and engineering activity, and of his great effort to direct the results of fundamental scientific investigations to solving the urgent problems of the society.

For over 60 years B.E. Paton has been heading the world-recognised R&D centre — the E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine — and already more than 50 years 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. By origin he came from known noble family of Paton, the tradition of which was service for the Motherland and military service. His great-grandfather, Peter Ivanovich Paton, joined the army of M.I. Kutuzov when he was sixteen years old and participated in the Patriotic War of 1812. He was awarded the order and completed service as infantry general and senator of Russian Empire. Grandfather, Oscar Petrovich, military engineer, guard colonel, consul of Russian Empire. Father, Evgeny Oscarovich Paton, outstanding scientist and engineer, founder and head of the Electric Welding Institute, man of high civic duty, Hero of socialist Labour, participant of the Great Patriotic War of 1941–1945, contributed greatly to the victory over the fascism, awarded by military orders. Natalia Viktorovna Budde, the mother of Boris Evgenievich, originated from ancient noble family. She was a pupil of Froebelev Lady Pedagogical Institute. During the time of revolution, hard times of civil war and formation of the new state, in the years of Great Patriotic War she was the most devoted friend and assistant of Evgeny Oscarovich.

The manufacturing and scientific activity of B.E. Paton started at the Uralvagonzavod Plant in Nizhnij Tagil in 1942. Since that time, Boris Paton was working together with his father for 11 years; these 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 pupils and worthy successor of his father. He continued and brilliantly developed the work started by E.O. Paton.

Along with a large and intensive work at defence factories, the team of the Institute continued the research works. In 1942, V.I. Dyatlov discovered the phenomenon of self-regulation of electrode melting in electric submerged-arc welding. The further investigation of this phenomenon by B.E. Paton together with A.M. Makara, P.I. Sevbo and M.N. Sidorenko allowed the design of a simple and reliable automatic welding machine. The application of automatic welding machines could increase by many times the efficiency of jobs in manufacture of tanks.

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 the tank crews were saved thanks to the reliable welded armour.

For the achievements in mechanization and automation of welding operations in fabrication of military equipment, B.E. Paton was awarded the Order of the Red Labour Banner in 1943.

During war years Boris Evgenievich carried out a number of important investigations of static properties of automatic machines for submerged-arc welding, becoming the basis of his thesis for a Candidate of Technical Sciences degree, which he defended in 1945. In the later studies he showed that optimum characteristics are typical of the automatic machines with a constant speed of wire feed, completed with power sources having a quick-response voltage controller.

For the development of semi-automatic machines for submerged-arc welding, B.E. Paton, specialists of the Electric Welding Institute and also «Elektrik» plant in Leningrad were awarded Stalin Prize in the field of science and technology in 1950. Later this principle of control was used as a basis for design of semi-automatic machines for shielded-gas welding.

B.E. Paton was working fruitfully on completing investigations connected with conditions of stable burning of arc and its control. He successfully defended his thesis for Doctor of Technical Sciences degree and was elected a Corresponding Member of the Academy of Sciences of the Ukrainian SSR in 1951.

In these years the investigations of welding power sources were made under the supervision of B.E. Paton. The topicality of these works was predetermined by the fact that the automatic submerged-arc welding was one of the most high-efficient processes and industry had a great need in new developments in this field. And the Institute started the comprehensive studies of metallurgical processes of submerged-arc welding. For a short period of time the fundamentals of theory of metallurgy of submerged-arc welding and surfacing were created, a series of different-purpose fluxes was developed. New technologies and powerful production of fused fluxes were developed.

Basing on these developments the first in the country production of high-quality large-diameter pipes was implemented at the Khartsyzsky Pipe Plant. B.E. Paton is one of the founders of this production. This work was a fundamental basis for organizing and development of up-to-date mass production of large-diameter pipes for powerful gas-transportation systems of the USSR at Khartsyzsky, Chelyabinsky, Volzhsky,Vyksunsky and other plants.

At the Institute a new process of submerged-arc welding of joints, located in different spatial positions, was developed. For the first time the method was applied for erection of span structures of the Kiev Bridge across the Dnieper River, which was named after Evgeny Paton, the chief ideologist of welded bridge construction and technical supervisor of designing and construction of this unique structure. Later on, the method for flux-cored wire arc welding with a forced weld formation was developed, which was widely applied in construction of span structures of the Moskovsky and Yuzhny bridges across the Dnieper River in Kiev, a bridge across the Volga River in Saratov, in construction of main pipelines, metallurgical facilities, chemical apparatuses and ship hulls.

After the death of Paton Evgeny Oscarovich in 1953, Boris Paton was appointed to the post of the Director of the E.O. Paton Electric Welding Institute of the Academy of Sciences of the Ukrainian SSR.

Boris Paton developed the planned organizing of research works of the Institute. He established business contacts with head officials of enterprises, National Economy Councils, Ministries, and GOSPLAN of the USSR. He organized and headed the preparation of proposals about 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 the resolution «On Further Industrial Application of Welding Engineering». The resolution envisaged the progress of fundamental research 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. Other similar resolutions were adopted during the five-year periods that followed. Their implementation predetermined the progress of welding science and technology in the second half of the 20^{th} century not only in the USSR, but also in a number of foreign countries. The USSR became the leading country in 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 work with people. He is always ready to support an interesting idea and estimate a work done at its true value. His genuine enthusiasm, rare capacity for work and attention to every staff member create a good creative atmosphere at the Institute. An example of this is the development of electroslag welding. G.Z. Voloshkevich, associate of the Institute, discovered that the molten slag, through which the electric current is passed, can serve as a source of heating the metal being welded. The process was called the electroslag one. Boris Paton could predict a great future for this process. The efforts of the working team were concentrated by him for the solution of the most important problems of electroslag welding. In the shortest time a new promising method for welding heavy sections of metal was developed, which was tested under production conditions and made ready for the wide implementation.

Application of electroslag welding radically changed the technology of production of such components as drums of high-pressure boilers, frameworks 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 were considerably more cost effective.

In 1957, B.E. Paton and G.Z. Voloshkevich were awarded the Lenin Prize for the development of the electroslag welding process and manufacture of large-size special-purpose parts on its basis. This achievement was marked by the Grand Prix in 1958 at the International Exhibition in Brussels.

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

In the opinion of Boris Paton the 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 directs the team of the Institute to the solution of actual problems in this area.

By the initiative of B.E. Paton the processes of formation of welding aerosols were investigated and a new generation of low-toxic welding electrodes was developed. The wide implementation of this development allowed improving radically the labour conditions, reducing greatly the professional deceases of welders. In the 1950s, the Electric Welding Institute started developing a new area, namely the automation and mechanisation of the processes of hard-facing the surfaces 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 under flux, in shielding gases, using self-shielding flux-cored wire and plasma jet. Unique surfacing equipment, consumables and technologies were developed. Industrial manufacture of surfacing flux-cored wires was organized. This area proved to be highly promising and the Institute is still active in it, and the technologies are widely applied in different branches of industry and construction.

In 1958, Boris Paton initiated the development of new methods for mechanized welding of structures under the field conditions, at erection sites, on building berths, and under the water, and suggested to apply the flux-cored wire for these purposes. A large complex of studies of metallurgical and technological peculiarities of this method of welding was carried out. A series of self- and gas shielding flux-cored wires of different purposes was developed and production of flux-cored wires was organized. 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 up the new opportunities for exploration of the continental shelf, construction and repair of port systems, pipeline transitions across rivers and other objects.

Boris Paton made a great contribution to the development of flash-butt welding. For the first time the effect of short-circuit resistance of machines for flash-butt welding on stability of melting and weldability of metal was studied. The high efficiency of welding current feedback was found. The unique designs of transformers were suggested and theoretical bases of their calculation were developed. Systems of multifactor control of the flash-butt welding process were developed for the first time in the world practice under the supervision and at the direct participation of B.E. Paton. Several generations of ingenious machines were designed, which have been in use for a few decades in many countries throughout the world. Among them are the rail welding machines, unique inside-pipe flash-butt welding machines «Sever», machines for welding of rocket elements made of aluminium alloys and many others.

The application of electron beam occurred to be challenging in welding of different thick-walled vessels of steels, high-strength alloys on aluminium and titanium base, and also other materials. The complex tasks were solved for providing the stability of electron beam in atmosphere of metallic vapours, peculiarities of formation of narrow and deep welds were revealed, the control methods were found providing the reproducibility of optimum welding conditions. All this allowed designing equipment and developing technologies, having the world recognition. The method of arc welding by tungsten electrode along the layer of activated flux-paste, named later A-TIG, was developed at the E.O. Paton Electric Welding Institute in the middle of the 1960s. Due to evaporation of the flux-activator it is possible to constrict the arc column, several times increase the penetration depth, increase the welding efficiency and improve the shape of welds. In the recent years B.E. Paton initiated the investigations directed to the creation of theoretical fundamentals of arc welding processes using activating fluxes. The main regularities of arc constriction influence on characteristics of thermal and dynamic effect on welding pool were established and mechanism of deep penetration of metal was explained. This unique technology found the further development in the USSR and CIS. The «Paton» technology PATIG was also recognized in the foreign countries.

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 laser-arc plasmatrons of direct- and indirect-action were offered, and a series of plasmatrons of different technological purposes was manufactured. New processes of hybrid laser-plasma welding and surfacing were developed, including the process of hybrid laser-microplasma welding of metals of small thicknesses.

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

In the 1980s, B.E. Paton initiated investigations at the Institute on the methods of thermal spraying of coatings using gas-oxygen flame and arc plasma; equipment and consumables were developed to produce protective layers with different properties.

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

In 1979, the idea of depositing various metallic coatings on surfaces of elements of the space station and devices was successfully verified. Special unit «Isparitel» was designed, a versatile hand tool (VHT) for welding, brazing and deposition of coatings was manufactured. VHT was tested in the open space in 1984 by cosmonauts S.E. Savitskaya and V.A. Dzhanibekov. Then, a cycle of systematic multipurpose experimental investigations on optimizing structural elements and technology of construction of large-size orbital structures and objects followed. In 1986, a structure in the form of a dismountable girder was constructed in space («Mayak» experiment). In 1991, the brazing of elements of truss structures was performed for the first time and a unit was manufactured for deployment of multiuse solar cells in «Mir» orbital station.

Results of many-year investigations in the field of space technologies were described in monograph «Welding in Space and Related Technologies» by B.E. Paton and V.F. Lapchinsky, which was published in 1997 in Great Britain, and then summarised in book «Space: Technologies, Materials Science, Structures» edited by B.E. Paton and published in 2000.

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 former Chief Designer of rocket-space systems at RPC «Energiya», who had been working with S.P. Korolyov for many years, wrote: «*B.E. Paton belongs to that Grand Pleiad of Soviet scientists and designers that made the USSR in the years of its existence a mighty and great power... B.E. Paton is a prominent scientist of the 20th century. His distinctive and unique feature is to embody ideas into reality...*»

At the beginning of the 1970s the first samples of systems, using the experimental-statistic models of welding processes were manufactured under the supervision of B.E. Paton. The rapid progressing of these works led to the development of automatic systems of control of welding processes, equipment and mechanized lines with use of microprocessor engineering.

Under his supervision, a large complex of fundamental and applied studies was carried out in the field of static and cyclic strength of welded joints, their resistance to brittle and fatigue fractures, performance under conditions of low temperatures. Several famous constructions were created. They include, first of all, the E.O. Paton all-welded bridge across the Dnieper. Principles, approaches and design-technological solutions, optimized at its designing and construction, opened up the way to the wide application of welding in bridge construction. This bridge was recognized by the American Welding Society as a prominent welded structure of the XX century. Experience in construction of E.O. Paton bridge was used in construction of bridges across the Dnieper in Kiev (South, Moscowsky, Gavansky, Podolsky-Voskresensky, road-transport and railway), in Dnepropetrovsk and in Zaporozhye, as well as a bridge across the Smotrich River in Kamenets-Podolsk.

A striking example of the new approach to construction of welded structures of high factory readiness became the development of technology of uncoiling the coiled tanks for storage of oil and petroleum products, due to which the problem of restoration of tank park of the country, ruined during the World War II, was solved in the short terms.

In collaboration with Research and Design Institute (Ukrproektstalkonstruktsya) the projects and technologies of construction were developed, which were successfully realized in construction of unique TV towers in Kiev, St.-Petersburg, Erevan, Tbilisi, Vitebsk, Kharkov. The monument «Motherland» in Kiev should also be referred to the outstanding welded structures.

B.E. Paton is initiator and scientific supervisor of the purposeful research-technical program «Problems of Life and Safe Operation of Structures, Constructions and Machines». Many academic and branch institutes, higher educational institutions and a large number of industrial enterprises were involved into accomplishment of this program. Important scientific-technical and practical results were obtained for the working out of methodological bases, technologies, methods and means for evaluation, and also for extension of service life of structures. The plans of Academy envisage the further development of these works.

A large attention is paid to the development of methods of non-destructive quality testing and diagnostics. Available are the automatic units for ultrasonic testing of welded joints of large-diameter pipes, bodies of drilling bits, components of power equipment, welded joints of light alloys and non-metallic materials. The studies with applying of low-frequency ultrasonic waves and contactless introduction of acoustic waves into test objects are underway.

For the first time in Ukraine the systems of continuous monitoring of welded structures, to which the increased requirements to safe service are specified, have been developed.

Methods of prediction of mechanical properties, life of safe service of welded joints and components in the presence of crack-like defects in them and degradation of materials during service have been developed.

Over many years the investigations on materials science are carried out at the Institute. New structural materials and technologies of their production are developed, the link «composition-structure-properties» is investigated as applied to different-purpose materials. The Institute became a large materials science centre, in which the highly-qualified specialists on metal physics, metals science, electron microscopy, mass-spectroscopy, Auger-spectrometry, gases analysis in metals and welds, X-ray spectral element analysis and other specialties are working and carrying out the most complicated materials science investigations.

In 1954 B.E. Paton headed the investigation on applying the electroslag process for improvement of quality of metals and alloys. This resulted in the radically new direction of metallurgy, namely electroslag remelting, which found its wide application and world recognition for the shortest periods of time. It is used for improving the properties of heat-resistant, stainless, tool, ball bearing and other steels and special alloys. Metal of electroslag remelting is used at present in manufacture of rotors of powerful turbines, mill rolls, high-pressure vessels, stop valves of heat and nuclear stations, cast stamping tools and other critical products.

As far back as 1959 the works were started on refining of metals and alloys using electron beam. The electron beam melting occurred to be an effective method of improving the quality of special steels and alloys on nickel and iron base, effective technological process of producing extra-pure niobium, titanium and many alloys on their base.

Over the recent years the electron beam technology is successfully developed for producing titanium ingots. New high-strength titanium alloys, alloyed with aluminium, zirconium, niobium, iron, were developed and industrial electron beam cold hearth units were designed. Many of them have no analogues in the world practice.

Method, equipment and technologies of plasma-arc remelting of metals and alloys have been developed. The opportunities of application of plasma-arc technology were especially widened after the design of AC plasmatrons, that allowed increasing greatly the reliability of designs of melting units and power sources.

In the recent years the ladle treatment of metallurgical melts is widely used in the world metallurgical practice. At the E.O. Paton Electric Welding Institute the new types of flux-cored wires have been developed, which contain the highly-active elements for microalloying, modifying and desulphurization of steels and cast iron. Technology and equipment have been developed for manufacture of large-diameter flux-cored wires. These investigations were further developed at the I.N. Frantsevich Institute of Problems of Materials Science, Donetsk Polytechnic Institute and other institutes and enterprises. Today, the method of injection metallurgy is widely used at metallurgical plants of Ukraine and Russia. With its use the tens of millions of tons of steel melts were treated.

At the E.O. Paton Electric Welding Institute the investigations in the field of brazing of metals and alloys are successfully developed. New materials and technologies of brazing are used in manufacture of latticed wings of rockets and parts of aircraft engines, space and drilling objects.

In the post-war years the huge deposits of oil and gas were discovered in the USSR. They are mainly located in Central Asia, Western Siberia, North Urals and other remote regions. So, it was necessary to construct the high-capacity main gas and oil transportation systems to transport oil and gas to the western regions of the USSR and abroad.

Under the supervision of B.E. Paton a complex of works was carried out for the development of technologies and equipment for pipelines welding. Ingenious technologies and equipment for flash-butt position welding of pipes, namely complexes «Sever», were developed. More than 70 000 km of pipelines, including about 6 000 km of large-diameter gas pipelines, were welded under conditions of the Extreme North.

The unique technology of automatic arc position butt welding of pipes by using the self-shielding flux-cored wire with a forced weld formation, namely complex «Styk», was developed. Using this technology, more than 10 000 km of main gas and oil pipelines were constructed, such as: «Druzhba», «Central Asia–Centre», «Urengoy–Pomary–Uzhgorod», «Khiva–Beineu», «Shebelinka–Izmail», «Yamal–Western Border», «Yamal–Povolzhye», etc.

Professor Nikolai K. Baibakov, a major authority in the oil and gas complex of the country, outlined that «*Boris Evgenievich Paton, as the President of the Academy of Sciences of Ukraine, as Director of the E.O. Paton Electric Welding Institute had a tremendous influence on the progress of oil and gas construction, on the development of oil and gas industry of the former Soviet Union...*».

Boris Paton pays a great attention to the realization of achievements of the present science and technology in a practical medicine. In the 1990s he suggested to apply the methods of welding for joining of live tissues and organized a creative team with participation of associates of the E.O. Paton Electric Welding Institute of the NAS of Ukraine, A.A. Shalimov Institute of Surgery and Transplantation of NAMS of Ukraine, Central Hospital of SSU and other medical establishments. This cooperation has led to the development of a new method of joining (welding) of soft tissues, which allows quick cutting almost without blood and joining of biological tissues, preserving their vitality. Healing of wounds in this case occurs much quicker than in use of traditional surgery methods, operation duration is significantly reduced, blood losses are decreased, period of post-operation rehabilitation of patient is reduced. Methods of electric welding of live tissues are used in more than 50 hospitals of Ukraine, as well as in hospitals of Russia and Belarus. More than 100 000 different surgical operations has been successfully accomplished : in general, thoracic and paediatric surgery, oncology, urology, gynaecology, otolaryngology, treatment of internal organs and other directions of surgery. At the E.O. Paton Electric Welding Institute the up-to-date equipment for welding live tissues has been designed and its manufacture organized. More than 130 surgery procedures have been developed and applied in practice.

In 2004 the complex of works on welding live tissues, fulfilled under the supervision and active creative participation of Boris E. Paton, was awarded the State Prize of Ukraine in the field of science and technology.

The Institute has a fruitful cooperation with the A.A. Shalimov National Institute of Surgery and Transplantation, Donetsk Regional Antitumoral Centre, P.L. Shupik National Medical Academy of Post-diploma Education, A.A. Bogomolets National Medical University, Military-Medical Administration of SSU, Kiev City Centre of Electric Welding Surgery and New Surgical Technologies at Kiev City Hospital No.1, V.P. Filatov Institute of eye diseases and tissue therapy, N.M. Amosov National Institute of cardiac-vascular surgery, A.P. Romadanov Institute of Neurosurgery, Kiev City Hospitals Nos. 1, 12, 17, 18 and many other medical establishments of Ukraine.

B.E. Paton pays a large attention to the international activity of the Institute and its scientists. The E.O. Paton Electric Welding Institute is the permanent member of the International Institute of Welding (IIW) and European Welding Federation (EWF). Under Boris Paton supervision the journals «Avtomaticheskaya Svarka» («The Paton Welding Journal»), «Advances in Special Electrometallurgy», «Technical Diagnostics and NDT» are published and translated into English. This allows informing the scientific and technical community about the results of research and new developments of the Institute.

Dozens and hundreds of talented scientists and engineers have grown at the Institute. Among the Patonovites there are many academicians and correspondent-members of the NAS of Ukraine. The Institute associates defended more than 138 theses for scientific degree of Dr. of Techn. Sci. and more than 716 theses — for Cand. of Techn. Sci. Many works, mentioned above, are the efforts of large and amicable team, solidarity of which was greatly contributed by the personal features of B. Paton, its leader.

One of the main principles, set forth by E.O. Paton in foundation of the Institute and developed by B.E. Paton, is the carrying out of purposeful fundamental investigations and close cooperation of science with industry. This principle is continuously embodied into life during the 80-year history of the Institute.

The research departments of the Institute, designing department, experimental work shops, experimental design-technological bureau, engineering centres, experimental productions, pilot plants were organized during all the history of the Institute. They are the indispensable links of the system for organizing investigations and implementation of their results in industry.

Realization of this system allowed creating the unique structures, equipment, materials, technologies, implementation of which greatly influenced the progressing of many branches of industry: machine building, ship building, rocket-space complex, aircraft construction, power engineering, mining complex, metallurgy and chemical industry, systems of pipeline transport, building industry, etc.

Self-sacrificing efforts of the Institute staff members were highly appreciated by the government. The Institute was awarded by the Orders of Lenin, October Revolution, Labour Red Banner, and many Institute employees were awarded the orders and medals of the USSR and Ukraine.

Nine works, in which the Institute members were participated, were awarded the Lenin Prizes in the field of science and technology, 24 works were awarded by the State Prizes of the USSR, 34 works — by the State Prizes of the Ukrainian SSR and Ukraine.

The many-year self-sacrificing efforts of the Institute staff members under the leadership of B.E. Paton received the world recognition.

In 1962 B. Paton was elected a full member (academician) of the Academy of Sciences of the USSR. At the same year the scientists of the Academy of Sciences of the Ukr.SSR elected B.E. Paton the President of the Academy of Sciences of the Ukr.SSR (now the National Academy of Sciences of Ukraine). Profound understanding of the role of science in society, its aims and tasks, high international authority of scientist, devotion to the science, inexhaustible energy and moral standards, social and political activity, experience in management of large scientific staff became decisive arguments in election of Boris Paton to the post of the President of the Academy of Sciences of Ukraine. In accordance with the Charter of the Academy the election of its president is carried out each five years and Boris Paton was nine times re-elected to this post. At this key position his talent of the science organizer became even more evident. Under his leadership a new structure of the Academy of Sciences and its new Charter were developed, directed to the most rational use of scientific efforts and funds, their concentration to the solution of the most important fundamental problems of science, which have a decisive importance for the country economy.

By the initiative of B.E. Paton and at his active support in the system of the Academy of Sciences of the Ukr.SSR the dozens of new institutes and organizations, widening and intensifying the research in the most important scientific directions were established. Thus, in 1965 by the initiative of B. Paton an academic research centre was founded and university was opened in the city of Donetsk. Later on a number of other research centres of the Academy of Sciences of the Ukr.SSR were established, namely Western (Lvov), South (Odessa), North-East (Kharkov), Pridnieprovsky (Dnepropetrovsk) and Crimean (Simferopol), which fulfil the functions of regional inter-industry bodies for coordination of the scientific activity. He constantly tries to define clearly the scientific profile of each institute, takes care of them to become the leading one in its direction in republic, state and world.

The Academy of Sciences is the major scientific centre of the country, where research works on actual problems of natural, technical and social-humanitarian sciences are widely carried out. Establishments of the Academy take worthy positions in separate sections of mathematics, theoretical physics, physics of solid-body and low temperatures, in radio physics and radio astronomy, materials science, cybernetics and computer engineering, neurophysiology, molecular biology, microbiology and virology, genetic engineering and in a number of other areas of knowledge.

A pilot-production facilities are created in the Academy and new types of relations between science and manufacturing are developed.

In 1963 B.E. Paton was elected a Member of the Presidium of the AS USSR. His work in this position allowed him to become familiar with activities of institutes of the AS USSR, to study the experience of functioning of the Presidium of the USSR Academy and its departments.

The close cooperation between the AS Ukr.SSR, AS USSR, State Committee on Science and Technology, Russian Academy of Sciences, academies of sciences of Soviet Union republics promoted the progress in the Ukr.SSR of many new research directions, establishment of new institutes, consolidation of the international reputation of the Academy of Sciences of Ukraine.

Boris Paton initiated the organizing of large integrated scientific-technical programs on separate branches of industry, transport, communication and agriculture. While fulfilling these programs, the scientists of the Academy made great contributions directly into the solution of urgent problems of development of the country economy. This form of organization of the scientific activity was universally recognized.

B. Paton organized the Scientific Council at the Presidium of the AS USSR on the problem «New processes of producing and treatment of metallic materials», which united the scientists of academic institutions with specialists of many other establishments and promoted the progress of science about materials in AS USSR, RAS and NAS of Ukraine. Many scientists of materials science and metallurgy, actively working in this Council, were elected to the Academy of Sciences of the USSR and Russian Academy of Sciences by recommendation of B. Paton and made great contribution into the development of science about materials.

B. Paton profoundly understands the role and place of science in the solution of humanitarian problems of society progress. By paying the large attention to the development and implementation of updated technologies in industry, he simultaneously tried to obtain the grounded estimations of their effect on environment and humans. Under his leadership the large teams of scientists of the Academy fulfilled the prediction evaluating the negative ecological and social-economic consequences of large-scale draining and irrigative melioration in the Ukr.SSR, intensive use of chemical agents in agriculture, transfer of a discharge part of the Denube and Dnieper Rivers. B.E. Paton took a principle position in the problem of construction of the nuclear power station in the Chernobyl region. Unfortunately, the events of 1986 at the Chernobyl NPP, known to the whole world, confirmed completely his warnings.

The outstanding talent of Boris Paton as a leader, scientist and organizer were fully revealed during the memorable days of the Chernobyl tragedy. Teams of many institutes of the Academy of Sciences of the Ukr.SSR, its Presidium became involved in the activities on liquidation of consequences of the accident from the very first days. Hundreds of scientists, specialists of the Academy of Sciences, ministries, departments and enterprises of Ukraine took part in this work. B.E. Paton headed the preparation of proposals for decision-making authorities of Ukr.SSR and Governmental Commission of the USSR. Later on, in September 1997 B.E. Paton headed newly organized Advisory Board of independent experts at the President of Ukraine for the integrated solution of problems of the Chernobyl Nuclear Power Plant.

In 2004–2005 Publishing House «Academperiodika» of the NAS of Ukraine published two volumes of «Chernobyl 1986–1987». Documents given in this fundamental work describe objectively and rather comprehensively the role of the Academy of Sciences of the Ukr.SSR and self-sacrificing labour of teams of the Academy Institutes under the leadership of its President.

After disintegration of the Soviet Union and formation of independent Ukraine under conditions of long-term economic and financial crisis, which touched the Academy as well, the President of the NAS of Ukraine could preserve the Academy, its major scientific schools. It was managed at the legislative level to remain the Academy status as a supreme governmental scientific organization, to preserve principles of its academic self-administration, to realize its restructuring in accordance with new conditions, to direct the fundamental and applied research to the solution of urgent problems of the state formation.

New priorities were identified in the field of natural, technical and social-humanitarian sciences. A number of new institutes and centres of a social-humanitarian profile was organized.

As to directions of mathematics, informatics, mechanics, physics and astronomy, materials science, chemistry, molecular and cell biology, physiology, it was managed to preserve the world level of investigations. The contribution of scientists of the Academy to the development of fundamental and applied studies in Ukraine is growing. New technologies, materials, computer engineering have been developed, new deposits of minerals were discovered, etc.

Institutes of economy and forecasting, economic-legal investigations, problems of market and economic-ecological investigations, regional investigations, demography and social investigations, Ukraine studies, oriental studies, political and ethnic studies, sociology, Ukrainian archaeography and source studies, Ukrainian language and some other departments, institutes and centres have been organized and are now successfully working.

The Institutes of the Academy take an active part in the development of innovation program of development of economy of Ukraine, in study of its history, culture and language.

Organization of fundamental and applied studies is updating, priorities are defined in the development of separate scientific directions and inter-discipline investigations. Among them is the program «Nanosystems, nanomaterials and technologies», «Sensor systems», «Intelligent information technologies», «Hydrogen Power Generation», «Energy Saving», «Problems of Demography and Development of Mankind», etc.

Much efforts are applied by B.E. Paton in preserving and developing the international cooperation, foreign economic relations with businessmen of foreign countries.

Scientists of Ukraine participate in fulfilment of many international programs. The joint competitions of scientific projects with Ukrainian scientific-technological centre, Russian foundation of fundamental studies, Russian humanitarian scientific foundation, Siberian Department of Russian Academy of Sciences are carried out.

B.E. Paton is one of initiators of creation and preserving of common scientific space within the frames of CIS. In 1993 The International Association of Academies of Sciences (IAAS), uniting the National Academies of 15 countries of Europe and Asia was established. Already 20 years Boris Paton is its continuous President. Under his leadership the Scientific Council of IAAS on new materials is working.

Academician B.E. Paton is the Honorary President of the International Engineering Academy, member of the Academy of Europe, Honorary Member of the Roman Club, International Academy of Technological Sciences, Honorary Member of the International Academy of Sciences, Education and Arts, International Astronautic Academy, Foreign Member of the academies and scientific-technical societies of many countries. Dozens of domestic and foreign universities elected academician B. Paton an honorary Doctor, including M.V. Lomonosov Moscow State University, Taras Shevchenko Kiev National University, St.-Petersburg State Technical University, National Technical University of Ukraine «Kiev Polytechnic Institute», Moscow State Physical-Technical University, etc.

B.E. Paton carried out and continues to carry out 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 Supreme Soviet of the USSR, member of the Central Committees of the Communist Party of the USSR and Communist Party of the Ukr.SSR, he was a leader and member of different high committees and commissions. The list of his positions is very impressive. He is successfully working in these positions owing to the great personal responsibility to the state, people and his own conscience.

In addition, he is characterized by an outstanding self-discipline, efficiency, rare ability to distinguish exactly the main points and take immediately the right decisions.

When characterizing Boris Paton, academician Yu.S. Osipov, the ex-president of the Russian Academy of Sciences said: «*The life of B.E. Paton — in science, in the sphere of research organization and practical realization of scientific achievements, his public and state activity — is truly a great feat for the sake of the science progress and for the sake of the future*».

For his great services to the science and state, B.E. Paton was awarded high titles of the twice Hero of Socialist Labour, Hero of Ukraine. He is a knight of four Orders of Lenin, Orders of October Revolution, Labour Red Banner, Friendship of Nations, Liberty, Prince Yaroslav the Wise of the 1, IV and 5 degree, Orders «For the Services to Motherland» of the 1 and II degree and «Order of Honour» (RF), Order of «Friendships» (China), Order of Frantsisk Skorina and Friendship of people (Belarus), «Order of Honour» (Georgia), «Dostyk» (Republic of Kazakhstan), «Shikret» (honour) (Republic of Azerbaijan) and many other awards of CIS countries. B.E. Paton is the laureate of Lenin and State Prizes of the USSR and Ukraine in the field of science and technology. He was awarded by the International Prize «Global Energy». He was awarded by M.V. Lomonosov, S.I. Vavilov, S.P. Korolyov Gold Medals, A. Einstein Silver Medal of UNESCO and many other awards and decorations.

Boris Paton 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, great experience, international authority in science and society allowed preserving the scientific potential of Ukraine.

Boris Evgenievich Paton is the leader, fighter, creative personality, deeply decent and kind man, possessing fantastic energy and capacity for work, enormous experience, deep knowledge in many fields, and ability to learn continuously. He has a generous nature and quick analytic 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 Paton was born on the day of foundation of the National Academy of Sciences of Ukraine in 1918. In 1998 when celebrating the 80^{th} anniversary of the Academy and its President, the huge hall of the «Ukraine» palace applauded after announcement that B.E. Paton was the first person in the country to be awarded the title of the Hero of Ukraine.

Such a man is our dear Boris Evgenievich Paton!

Let us wish him from the bottom of our hearts new successes, strong health and a good luck.

I.K. Pokhodnya
Academician of the NAS of Ukraine

RESEARCH AND DEVELOPMENTS OF THE E.O. PATON ELECTRIC WELDING INSTITUTE FOR NOWADAYS POWER ENGINEERING

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Some developments of the E.O. Paton Electric Welding Institute for power engineering have been presented, in particular, technologies for welding of large-size turbine rotors, electron beam welding of thick billets of high-strength steels, technologies of submerged-arc welding and flash-butt welding with a pulsating flashing of pipes for main large-diameter gas pipelines, technology and equipment for manufacture of energy-saving heat-exchanging devices. Outlined are the developments, directed to increase in the corrosion resistance of fuel elements and safe service of NPP due to application of high-temperature wear-resistant mechanized surfacing of pipeline stop valves with corrosion-resistant alloys. Practical recommendations for repair of main pipelines without interruption of their operation are given. The investigations were carried out showing the possibility of application of acoustic emission for monitoring welded structures, operating at high temperatures. Method for prevention of catastrophic leakage of oil from damaged pipes of wells of oil-production platforms has been developed. 20 Figures.

Keywords: *submerged-arc welding, flash-butt welding with pulsating flashing, electron beam welding, protective coatings of fuel elements, ribbed plane-oval pipes, ultrasonic testing of welds, acoustic emission, wear-resistant surfacing, technical diagnostics*

The progress of power engineering defines in many respects the scales and rates of growth of the world economy. By the most prudent estimates the total energy consumption in the planet will twice increase in the XXI century. The generation of electric energy will grow most intensively (Figure 1), which by 2030 will reach 40 % of the world demand for the energy resources. Coal, oil and gas will remain the main source of energy in the nearest decades. However, their deposits are exhausted, and exploration of new ones will require significant investments. Moreover, the ecological consequences from the fossil fuel utilization are becoming the more and more threatening: atmospheric outbursts lead not only to the pollution of environment and deterioration of health of population, but also to the global changes in climate.

Today the efforts of the world community are directed to:

- increase in efficiency of power consumption;
- development of economically-grounded energy sources;
- reduction of harmful outbursts by applying new technologies and more ecologic types of fuel, such as natural gas, nuclear energy and renewable sources. Solution of these complicated problems, directed to the creation of the power engineering of future, depends more than ever on the research results, their quick and effective application.

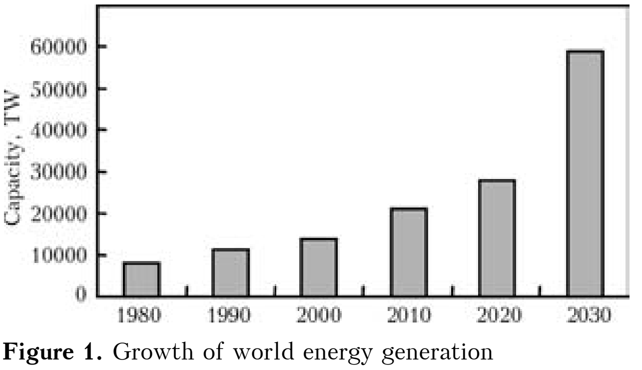


Figure 1. Growth of world energy generation

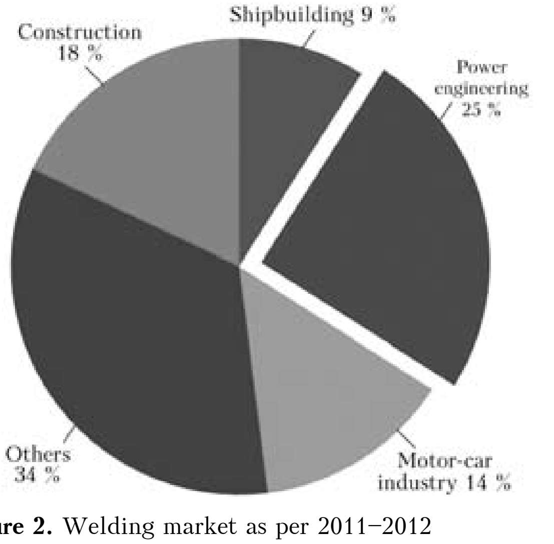


Figure 2. Welding market as per 2011–2012

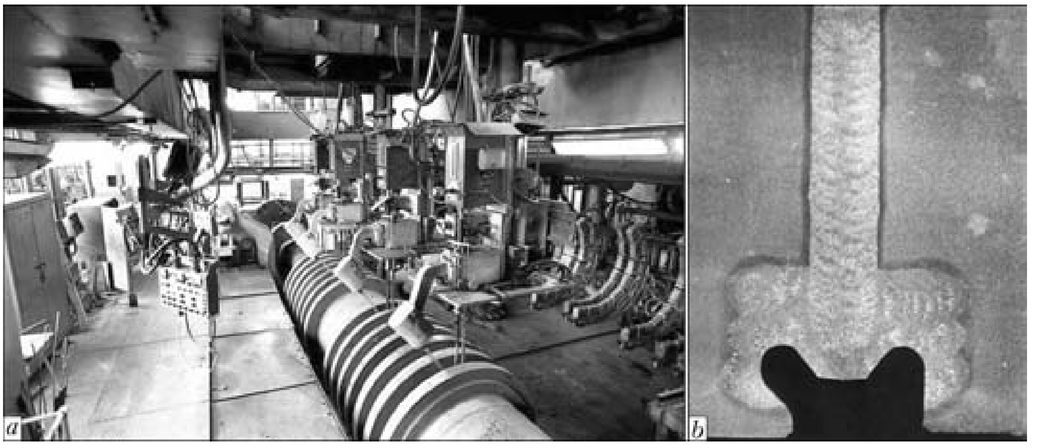


Figure 3. Automatic submerged-arc welding of rotor of steam turbine of 1000 MW capacity for NPP (*a*) and macrosection of weld metal of steam turbine rotor (*b*)

The scientists and specialists-welders make a great contribution to the development of energy-effective, ecologically clean technologies and products. The nowadays welding production is one of the science intensive inter-industry constituents of the world economy. In the industrialized countries more than a half of the national gross product is produced by application of welding technologies. The welding market, in spite of short-time declines in the period of world crisises, continues confidently growing. In 2012 the volume of world welding market was 17 billion USD and as to estimation of experts it will increase in the nearest five years up to 22 billion USD. Its largest share refers to the welding market in power engineering (Figure 2). It is predicted that it will increase by 30 % in the nearest three years.

Today there is a powerful arsenal of technologies, which allow producing permanent joints of different structural and functional materials.Welding technologies give opportunity to develop the unique designs of power equipment, such as turbines, power boilers, bodies of NNP reactors, etc.

The E.O. Paton Electric Welding Institute is fulfilling a large complex of works in the field of welding and related technologies for power engineering. As applied to turbine construction, the technology and specialized equipment have been developed and implemented in industry for assembly and automatic narrow-gap submerged-arc welding of large-size rotors of powerful steam turbines for heat and nuclear electric stations using one and the same assembly-welding stand. In this case the rotors of cylinders of low and medium pressure are manufactured of separate discs, thus excluding the rather difficult problem of producing large-size heavy all-forged billets for rotors of mass up to 200 t and length of more than 10 m. The installation for assembly and welding is completed by four machines for automatic submered-arc welding with a program control of the process of bead layout in a narrow groove and system of electrode tracking at the bottom and walls of the groove (Figure 3).

In manufacture of products of power machine building it is necessary to weld billets of thick high-strength steels. Electron beam welding (EBW) is rather effective in this case, providing high efficiency of the welding process, high quality of joints and minimum deformations. At the E.O. Electric Welding Institute the research and developments were made for creation of technologies and equipment for EBW of structural

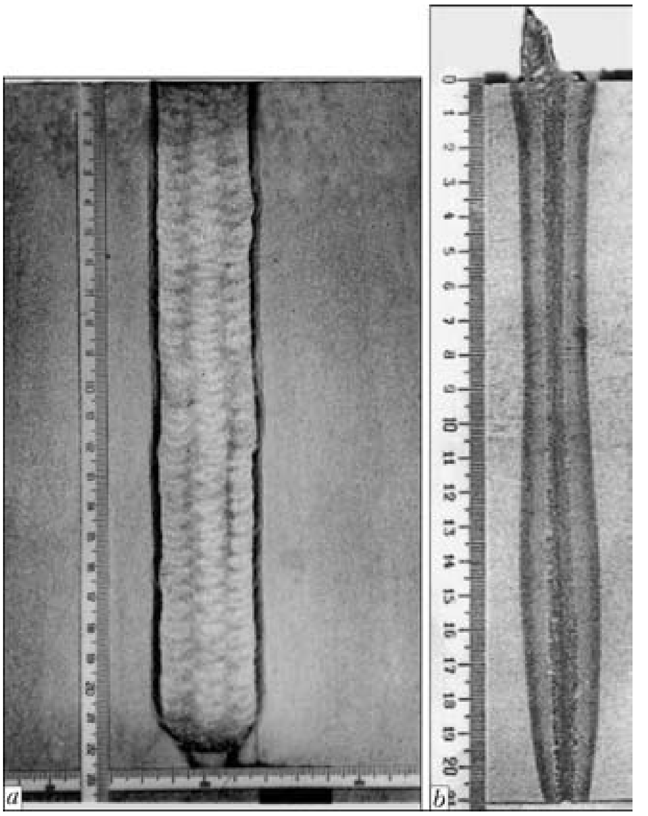


Figure 4. Macrosections of cross-section of low-alloy thick steel circumferential welds made by multilayer submerged-arc welding (*a*) and single-pass EBW (*b*)

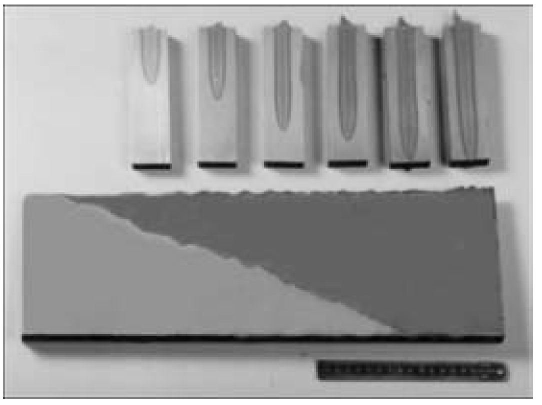


Figure 5. Macrosections of region of circumferential weld closing in EBW of 150 mm thick steel 15Kh2NMFA

steels of up to 210 mm thickness (Figure 4). Stable formation of welded joints and prevention of defects in metal of deep welds is attained by beam scanning with its parallel transfer along and across the welding direction.

The task of producing welded joints of high quality is significantly complicated at the area of the circumferential weld closing where the root defects are occurred. This task was solved by applying the beam scanning, beam focusing in the plane by 10 mm above the weld middle and inclination of butt plane and welding beam for angle 10° with respect to horizon. In Figure 5 the quality formation of rounding in weld root and complete absence of defects is well seen.

New generation of large-size vacuum chambers, technologies of their assembly and EBW has been developed (Figure 6). A principal distinguish feature of these chambers is the use of two vacuum-tight and strong shells joined between themselves by stiffeners. High geometric accuracy of chamber walls provides new possibilities in design of high-precision manipulators of gun and workpiece. To control the manipulators and all the process of welding, the software with a convenient graphic interface of the operator was developed.

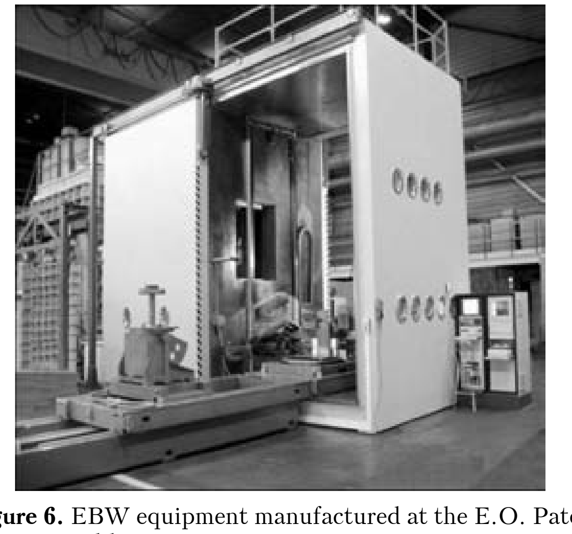


Figure 6. EBW equipment manufactured at the E.O. Paton Electric Welding Institute

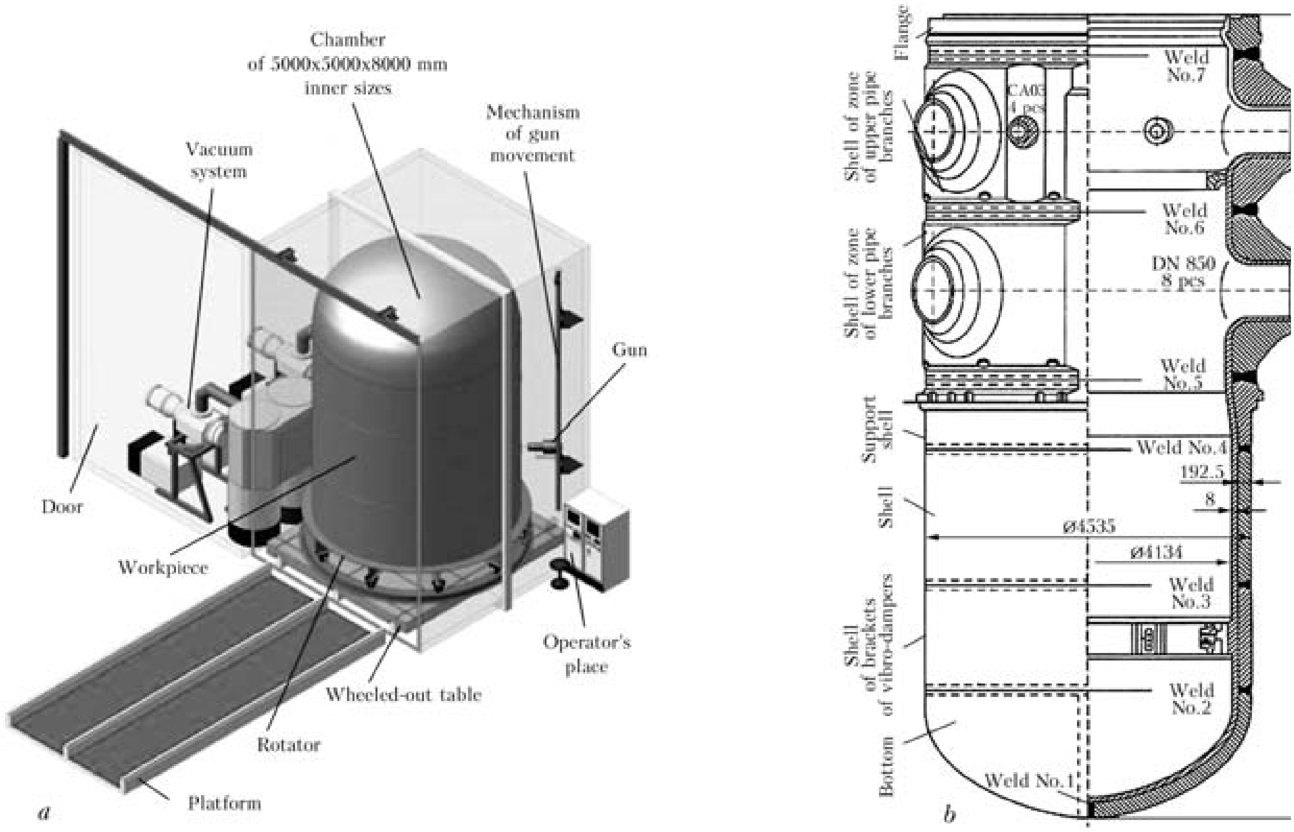
The developed technology of EBW of high-strength thick steels is challenging for its application for manufacture of NPP reactor bodies. As the practice shows, the duration of arc welding of circumferential welds in reactor body is hundreds of hours, while the EBW of such weld will take several hours, The schematic diagram of the offered industrial installation for welding circumferential welds of body of reactor WWER-1000 is shown in Figure 7.

The progress of the nuclear power engineering is indispensably connected with increase in safety of nuclear reactors and reduction of expenses for their service. The cause of emergency situation at the nuclear station Fukushima-1 was the chemical interaction of zirconium shells of fuel elements with a steam. Steam-zirconium reaction led to hydrogen generation, causing explosion.

One of the ways of reducing the expenses for NPP service is the increase in cycle of reloading of the nuclear fuel that also requires the increase in corrosion resistance of zirconium alloys in water under regular conditions of the reactor operation. Therefore, the development of methods and technology of manufacture of fuel elements, providing increase in corrosion resistance of zirconium shells in water and steam under regular and emergency conditions, is urgent.

One of the ways of solution of this problem is the application of protective coatings on the surface of zirconium shell of fuel elements, which should provide its longer service life under the regular condition and in case of emergency situation to reduce significantly the probability of occurrence of steam-zirconium reaction.

To solve the put problem the investigations were carried out, directed to the development of method of deposition of thick coatings on silicon carbide base on zirconium shells of fuel elements. The offered method is based on application of a high-speed electron beam deposition of thick coatings of inorganic materials, developed at the Institute. The use of powerful electron beam guns in stationary mode allows evaporation of metallic and ceramic materials in vacuum at high speed and to form coatings on their base having a preset structure. This method can provide deposition of coatings on the base of silicon carbide at the rates of 5–10 μm/min and to produce coatings on long shells of fuel elements at the rate of about 1 m/min. The distinguished feature of the developed method is the possibility of combining the process of coatings deposition with other processes which are necessary to provide high



Fugure 7. Schematic diagram of industrial installation for EBW of circumferential welds of body of reactor WWER-1000 (*a*) and scheme of reactor body (*a*)

strength of adhesion of substrate and coating, modifying the coating structure, etc.

The appearance of fragments of zirconium shells of fuel elements without coating and with coating is presented in Figure 8. The developed procedure of deposition provides the homogeneous defect-free coating along the surface with negligible roughness and high adhesion strength, high hardness, without defects both in the coating itself as well as at the coating-substrate interface (Figure 9).

The E.O. Paton Electric Welding Institute together with A.A. Bochvar VNIINM carried out investigations of corrosion resistance of coatings at high temperatures (emergency mode of fuel element operation), which showed their resistance to oxidation. As is seen from Figure 10, the coating during tests preserves integrity and a good adhesion with a substrate whereas the specimens without coatings undergo the intensive corrosion in uncoated area of the zirconium specimen at the same conditions.

The E.O. Paton Electric Welding Institute together with Kiev Polytechnic Institute has developed the technology and equipment for transverse ribbing of plane-oval pipes by the method of flash-butt welding and manufacture on their base of a wide assortment of energy-saving heat-exchanging devices (Figure 11). Transverse ribbing of the plane-oval pipes by the method of flash-butt welding has a number of indisputable advantages: high manufacturability without ap-

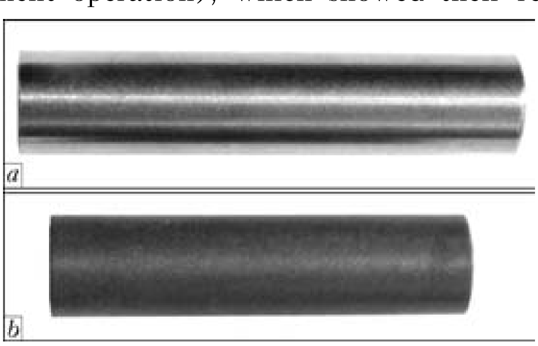


Figure 8. General view of fragments of zirconium shells without coating (*a*) and with coating (*b*) on silicon carbide base

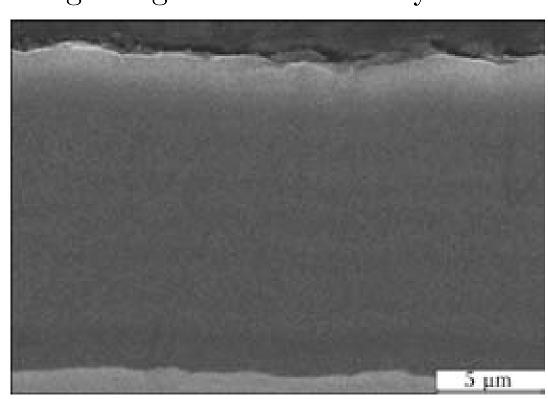


Figure 9. Microstructure of coatings on silicon carbide base

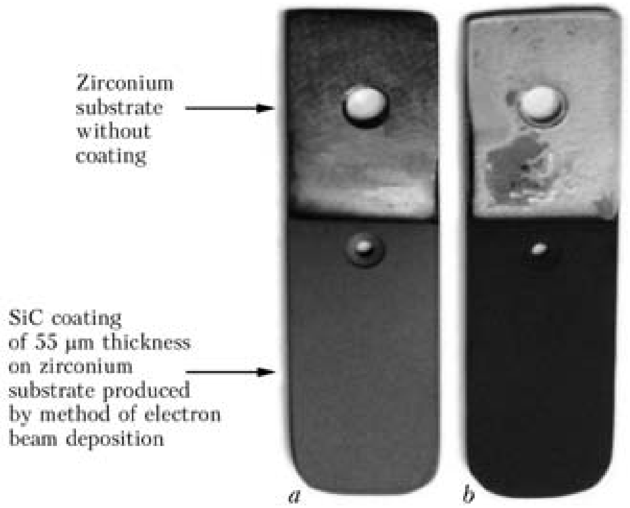


Figure 10. General view of zirconium specimens before (*a*) and after (*b*) testing the corrosion resistance of coatings at high temperature

plication of consumables; almost perfect thermal contact between ribs and a pipe; high intensity of convective heat exchange and low aerodynamic resistance. When updating the boilers of average and low capacity the application of economizers with plane-oval ribbed pipes is very efficient method of fuel saving. Moreover, a high economic effect is achieved in this case.

In connection with the growing need of world economy in power resources the problem of reliable transportation of hydrocarbon fuel from the regions of its extraction to the main consumers is very challenging. In spite of development of alternative methods (transportation of the liquefied gas by tankers or compressed gas in special vessels), the pipeline transport still remains the preferred method of natural gas supply to the consumers.

The new technology of submerged multiarc welding with a combined supply of arcs to improve the quality characteristics of welded joints due to optimization of arcs phasing, conditions of their burning and set-up parameters of electrodes was investigated. For series manufacture of pipes, the 4- and 5-arc welding processes with the current of front arc increased up to 1900 A have been designed, which allowed reducing the groove sizes, increasing the welding speed and decreasing the consumption of welding consumables (Figure 12). The additional advantage in this case is favorable configuration of fusion line, which improves test results on impact bending of metal of welded joints, especially of thick-wall pipes. The technology is recommended for welding of pipes with wall thickness from 25 to 50 mm.

During manufacture of pipes of small and average thickness of a wall it is possible to apply the multiarc welding with electrode of smaller diameter (3.2 mm) at the first arc, characterized by deep penetration, sufficiently favorable weld formation and some decrease in energy input.

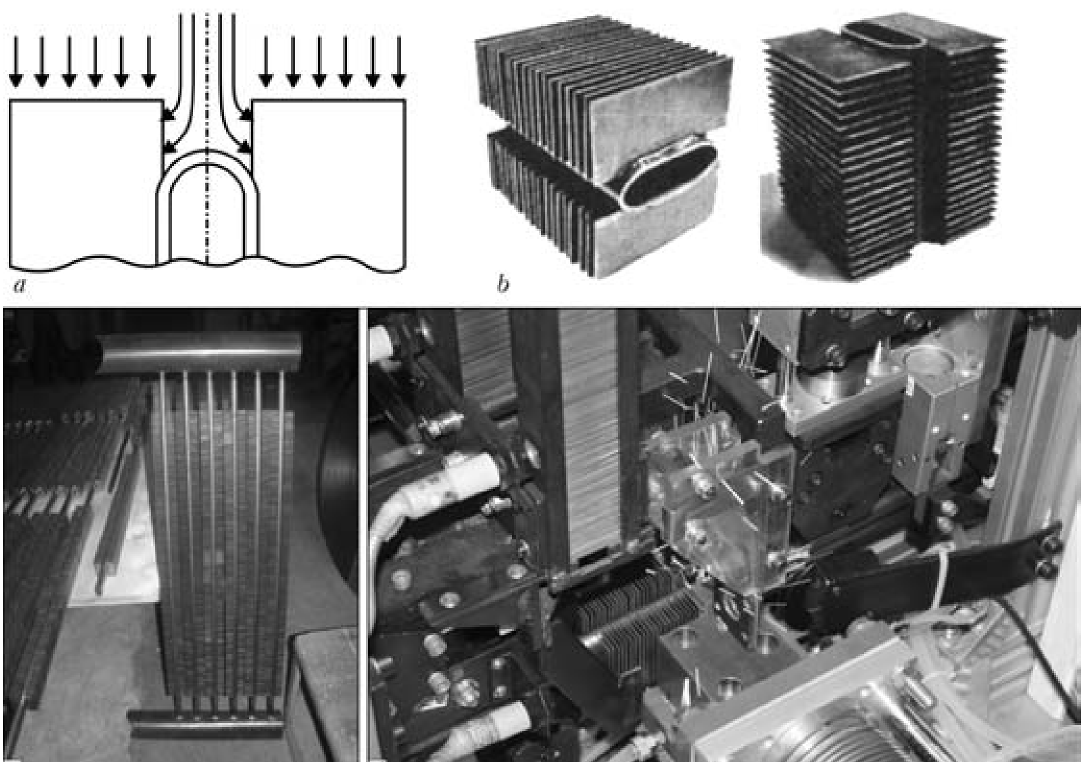


Figure 11. Plane-oval pipes with a transverse ribbing for energy-saving heat-exchanging devices: *a* — scheme of heat carrier flow; *b* — pipe elements; *c* — section of economizer-disposal unit of 0.2 MW capacity; *d* — automated installation for flash-butt welding of plane-oval pipes

To provide high values of toughness the system of control of chemical composition and structure of weld metal of pipes was developed at the Institute. It is based on application of submerged multiarc welding, where welding wires of different chemical composition are set at separate arcs, that allows dosing control of content of alloying elements in weld metal at a high accuracy depending on composition of applied pipe steel, welding conditions and other factors. During manufacture of pipes the combination of agglomerated aluminium flux of low basicity and welding wires containing manganese, molybdenum or manganese, nickel, molybdenum, or manganese, molybdenum, titanium, boron. The required chemical composition of weld is attained by change in number of arcs with welding wire of any alloying system and different speed of its feeding at separate arcs. The control of chemical composition of pipe weld metal provides the most favorable its structure. Figure 13, *c* shows microstructure of metal of longitudinal weld of gas and oil pipe of 1420 mm diameter with 25 mm wall thickness, made of steel of K60 strength class (category X70), composed of 85–90 % acicular ferrite and less than 1 % of intergranular polygonal ferrite. Such structure guarantees high tough characteristics of weld metal, for example, impact toughness in the limits of 180–200 J/cm^2 on the specimens with a sharp notch at temperature of –30 °C.

The developed combination of welding consumables and new processes of multiarc submerged welding, also that with increased current of front arc, including recommendations on optimization of conditions and set-up parameters, were realized at different pipe welding plants of Ukraine and Russia in manufacture of pipes with wall thickness from 16 to 40 mm of steel of K60-K65 strength class (category X70-X80) for main pipelines.

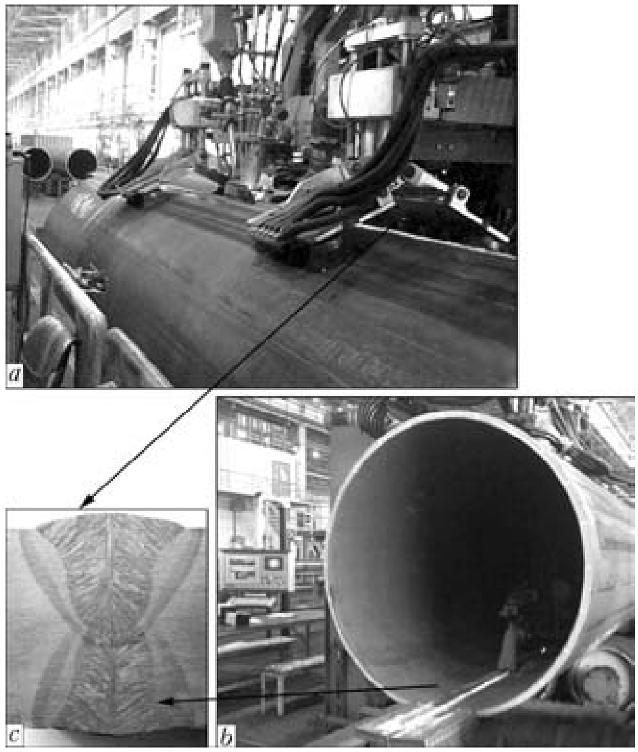


Figure 12. Multiarc submerged welding of 1420 mm diameter pipe of 40 mm wall thickness: *a* — 5-arc welding of external weld, 110 m/h speed; *b* — 4-arc welding of inner weld, 110 m/h speed; *c* — macrosection of pipe welded joint

During construction of main pipelines the E.O. Paton Electric Welding Institute together with the organizations of OJSC «Gazprom» gained great experience in application of position flash-butt welding of pipelines under field conditions in different climatic regions, in particular in the regions of the Extreme North. Using complexes «Sever» (Figure 14) and other flash-butt

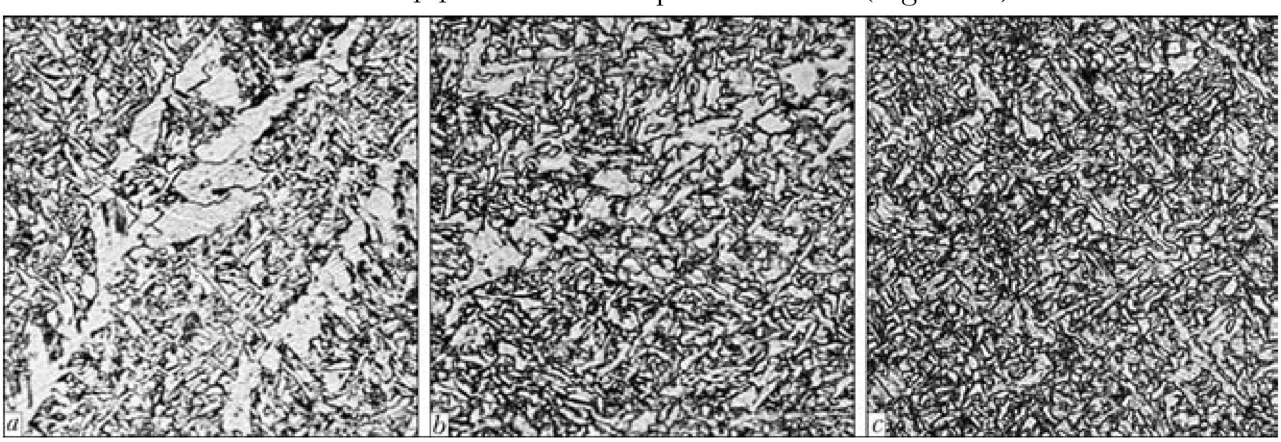


Figure 13. Microstructure (×500) of weld metal of pipes of K60 strength class steel, produced by applying different welding consumables: *a* — Mn–Mo system of alloying, acid fused flux, polygonal ferrite is 20–25 % ; acicular ferrite is 35–45 %; KV_{-30} = 27–30 J/cm^2; *b* — Mn–Ni–Mo system of alloying, aluminate agglomerated flux of low basicity, polygonal ferrite 3–5 %, acicular ferrite 75–80 %; KV_{-30} = 80–100 J/cm^2; *c* — Mn–Mo–Ti–B system of alloying, aluminate agglomerated flux of low basicity, polygonal ferrite of less than 1 %, acicular ferrite 85–90 %; KV_{-30} = = 180–200 J/cm^2

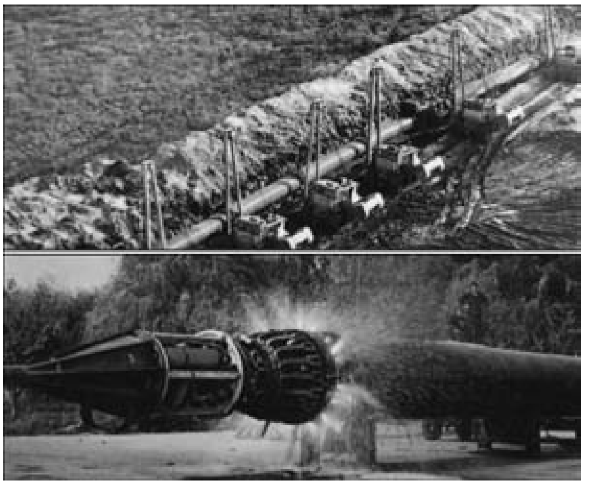


Figure 14. Complex «Sever» for pipe welding of main oil- and gas pipelines

welding machines, more than 70 000 km of different pipelines including those of large diameter were welded which are now successfully operating.

At the present time the Institute is developing the new process of flash-butt welding of pipes with a pulsating flashing (FBW). Its novelty consists in the fact that due to application of quick-response systems for control of welding machine and new algorithms of control a great intensification of heating is possible at the same installed capacity of electric power source.

The process of pulsating flashing has a number of advantages as compared to the continuous flashing. Thus, the mode of welding using pulsating flashing reduces the time of welding of circumferential butt as compared to the continuous one from 3.5–4 min to 2 min, and tolerance for flashing is decreased almost twice. The latter is very important since losses of metals are significantly decreased. Due to the use of systems of automatic control of flashing speed it was managed to obtain the quality welding at lower values of specific power, than that in welding of pipes using complexes «Sever». Therefore in welding of pipes of 1420 mm diameter with 27 mm wall thickness the source with installed peak power of up to 1300 kV/A is applied.

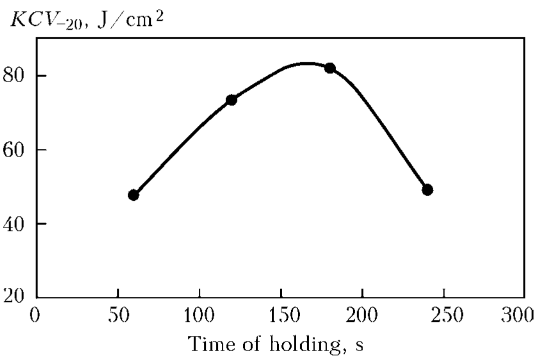


Figure 15. Dependence of average values of impact strength on holding time at 1000 °C temperature of heat treatment

In accordance with the requirements of international standards API1104 and DNV-OS-F101 the mechanical properties of welded joints were determined in the state after welding and heat treatment. Thus, in the as-welded state the strength values (σ_t = 516.0–523.6 MPa) and bending angle (180° at the absence of cracks) meet the set requirements, whereas impact toughness is lower than the standard requirements (KCV_{+20} = 13.3–17.1; KCV_{-20} = 6.1–9.7 J/cm^2) because of the presence of a coarse-grain structure with increased ferrite content in the heat-affected zone.

To increase the impact toughness, the technology of heat treatment of joints, made by FBW, using a postweld local induction heating, was developed. Mechanical properties of welded joints in as-heat treated state were as follows: (σ_t = 550.6–561.4 MPa, bending angle is 180°, KCV_{+20} = 147.9–219.5, KCV_{-20} = 86.8–171 J/cm^2. It was found that the highest values of impact toughness of welded joints, made by FBW on steel of K56 class of strength, can be obtained at temperatures of normalization 950–1000 °C and duration of heating within 2.5–3.0 min (Figure 15), and cooling after heating should be performed at the rate of not less than 8 °C/s.

At tests of reference batch of joints, made at optimum condition with next heat treatment, the quality of joints meets completely the requirements of standards.

Simultaneously with the development of the welding technology, the algorithms of revealing defects in joints, made by FBW, were determined using means of updated ultrasonic flaw detection. Systems and algorithms of in-process computerized control of welding parameters were also developed, which allow evaluating joint quality just after welding completion. Moreover, the automatic system provides a printed document for each butt, indicating real values of all welding process parameters, their deviations from those preset by program and quality of joints.

Technology of nondestructive testing of thick-wall pipe circumferential welds, made by FBW, was developed. Technology is based on applying the echo-mirror method of ultrasonic testing which is realized using transducers connected in tandem.

It is characteristic that defects in FBW are located in one plane of the joint. At FBW of thick-wall pipes this plane is always normal to the pipe axis that facilitates the detection of defect location where it is not necessary to account for all the signals from structural heterogeneity of metal, coming from regions which are located beyond the joint plane. Two categories of defects are distinguished which can be revealed by the ultrasonic testing: defects due to chemical heterogeneity of metal and defects caused by violation of welding conditions. Algorithms of evaluation of defects of joints, made by FBW, are determined which are harmonized with references at UST of joints made by electric arc welding methods.

As a result of these investigations, the technology of nondestructive testing of pipe joints, made by FBW, which is required in accordance with standards as an obligatory operation, was certified.

As a result of carried out investigations, the E.O. Paton Electric Welding Institute in collaboration with «Pskovelectrosvar» plant designed a complex of equipment for FBW of offshore pipelines of 1219 mm diameter and 27 mm wall thickness for application in pipe laying barge (Figure 16). The complex has been manufactured and is at the stage of testing.

The service reliability of operation of heat and nuclear power stations depends greatly on leaktightness and high wear resistance of sealing surfaces of the pipeline stop valves. Erosion and corrosion wear, thermal fatigue cracks, as well as appearance of burrs on the friction surfaces are the main causes of the pipeline stop valves coming out of order.

Materials, technology and equipment were developed for mechanized surfacing of parts of power pipeline steam-water high-parameter stop valves of all the types and sizes. Surfacing with high-temperature wear- and corrosion-resistant alloys is widely used, that allowed significant extension of service life of stop valves and increase of its reliability. The improvement of processes of surfacing the stop valve sealing surfaces will be realized by its automation and development of new wear-resistant alloys.

At the Institute, the practical recommendations have been worked out for the repair welding of pipelines without interruption of their operation. These recommendations include a complex of procedures and engineering instructions for evaluation of state of main pipelines with revealed defects, as well as for planning the repair by pressure welding. As applied to typical defects of main pipelines (local and general corrosion damages of metal, cracks, shape defects), the criteria are offered for evaluating their admissibility from the positions of a degree of decreasing the load-carrying capacity of the pipeline both in service and also during repair (Figure 17). A special attention is paid to the problems of planning the repair works using different supporting structures, such as: welded bands, sealing couplings, couplings with a compound filler.

Figure 16. Complex for flash-butt welding of offshore pipelines of 1219 mm diameter and 27 mm wall thickness

As the equipment for heat and nuclear power stations is operating at high temperatures and pressures, then the application of traditional means of nondestructive testing in service is impossible. Therefore, it is necessary to develop methods and means for monitoring of technical state of power engineering objects. Investigations were carried out, which showed for the first time the possibility of application of methods of acoustic emission for this purpose. Figure 18 gives diagrams of tensile tests of specimens of steel 15Kh1M1F at room temperature and 500 °C. As is seen, the acoustic activity is preserved at all the stages of material deforming at high tempera-

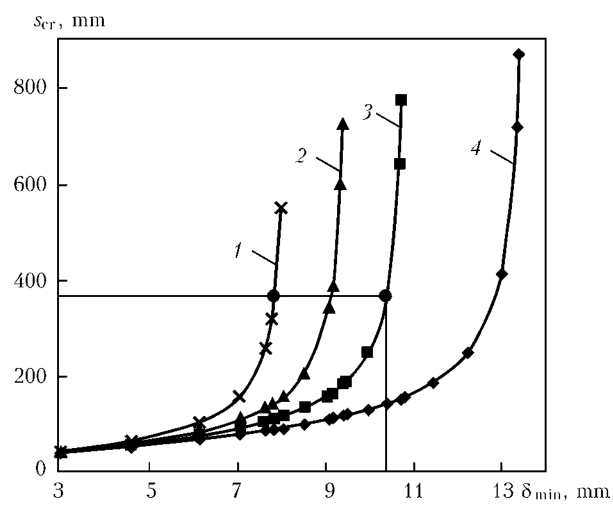


Figure 17. Dependence of critical length of defect of a local thinning type s_{cr} on minimum allowable thickness δ_{min} of wall of 1420 × 20 mm pipe of steel 17G1S at different internal pressure: *1* — 4.5; *2* — 5.25; *3* — 6.0; *4* — 7.5 MPa

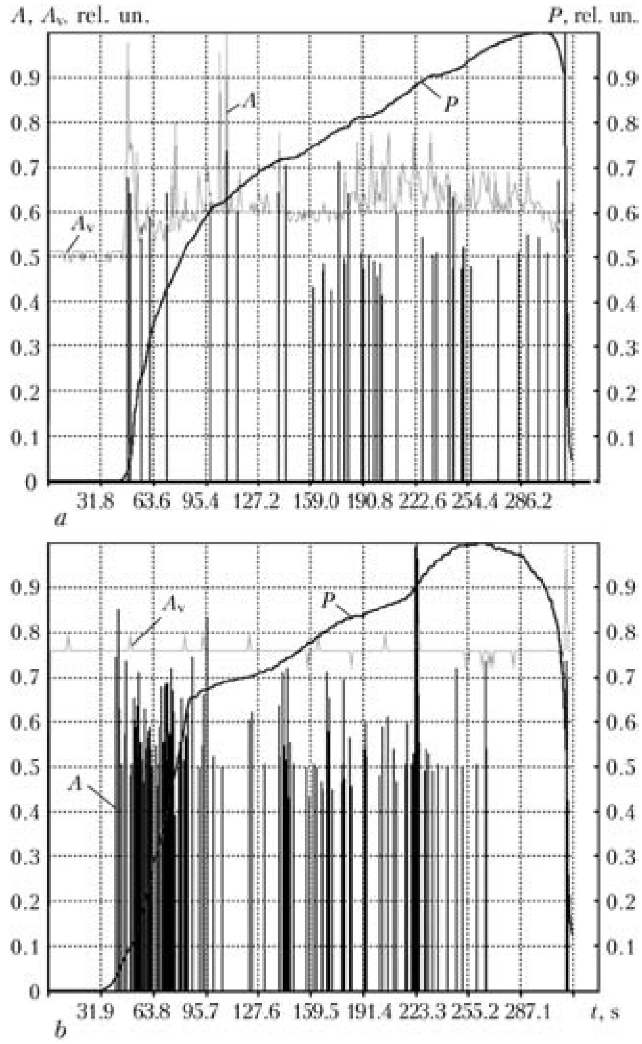


Figure 18. Comparison of signals of acoustic emission in tensile specimens of steel 15Kh1M1F at room temperature (*a*) and 500 °C (*b*) (A — amplitude; A_v — amplitude of continuous emission; P — loading)

ture, thus allowing prediction of fracture loads with a sufficient validity.

«Program of works of continuous acoustic-emission monitoring in equipment of HES «Kievenergo» has been developed and realized. At the first stage the diagnostic reference parameters of pipelines of hot intermediate overheating, preheaters of high pressure and deairators were investigated, system of continuous monitoring of pipelines of intermediate overheating was designed and assembled. System was put into experimental service (Figure 19). Decision was taken for implementation of means and technology of continuous acoustic-emission monitoring of equipment of other HES.

As is known, accidents at oil-gas productions lead to drastic ecological consequences. One of such accidents occurred in 2010 in Gulf of Mexico at oil production platform, where uncontrollable leakage of oil took place from damaged well at the 1500 m depth. Specialists of the Institute developed a method of joining the damaged pipes of wells during oil leakage. A connecting module was designed and manufactured, which passed successfully the tests (Figure 20). Functional scheme of its operation is as follows. Using hoisting mechanisms the module is lowered to a damaged part of the well. It is clamped by technological devices which maintain module in vertical position and do not give opportunity of coming out flow to remove it aside. Moreover, there is now dynamic shock and detachment of module from the place of fixation due to necessary holes available in the module design, which provide a free flowing of intensive oil flow into surrounding environment. Then these module holes are closed. For this purpose, the hydraulic cylinders and special shutters are used, envisaged by the module design. After completion of operation of hydraulic cylinders and closing of module holes the oil is directed into a required direction along the pipeline.

Figure 19. One of points of measurement by AE of operation activity of pipeline of steam intermediate overheating at Kiev HES-6

Figure 20. Module for joining the damaged pipes of wells

Such are the developments of the Institute, designed for the nowadays power engineering. Investigations and development of new technologies are continued.

Received 01.07.2013

STRATEGIC TRENDS OF DEVELOPMENT OF STRUCTURAL MATERIALS AND TECHNOLOGIES OF THEIR PROCESSING FOR MODERN AND FUTURE AIRCRAFT ENGINES

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Strategic directions of development of materials and their processing technologies for the main parts of new generation GTE are determined for the period up to 2030. Modern tendencies of development of cast and wrought heat-resistant alloys are described, including nickel- and titanium-base intermetallic alloys. Characteristics of new vacuum equipment mounted at FSUE «VIAM» for melting of heat-resistant alloys and deformation of high-temperature materials under the conditions of isothermicity in air are given, as well as the results of developments in the field of ion-plasma deposition of protective high-temperature, strengthening and thermal barrier coatings on blades and other GTE parts and development of a new generation of plasma-chemical equipment. Technology of producing a wide range of superpure ultradisperse powders by the method of atomization for vacuum diffusion brazing and additive technologies has been developed. 24 Ref., 10 Figures.

Keywords: *materials and processing technologies, gas turbine engine parts, cast and wrought heat-resistant alloys, intermetallics, vacuum equipment, blades, technologies of ion-plasma spraying of coatings, manufacturing superpure powders*

Analysis of progress of science and technology in the field of development and application of alloys and steels with special properties, formed world tendencies, as well as raw material and resource capabilities demonstrate the urgency of the problem of development of a package of technological solutions for creation of a new generation of cast and wrought alloys and steels with special properties, including complex protection systems and thermal barrier coatings.

Main principles of development of modern materials for complex technical systems should be based on the results of fundamental and fundamentally-oriented research, derived by leading research organizations in cooperation with the Institutes of RAS and on the following postulate: inseparability of materials, technologies and structures, including application of «green» technologies in development of materials and complex protection systems, as well as realization of a full life cycle (with application of IT technologies) — from material development to its operation in a structure, diagnostics, repair, service life extension and recycling.

Considering priority directions and critical technologies in development of science, technology and engineering in the Russian Federation, approved by the Decree No. 899 of President of the Russian Federation of July 7, 2011, priorities in state policy in the industrial sphere, development strategies of state corporations, and integrated structures for analysis of tendencies in materials development in the world, FSUE «VIAM» determined the following strategic directions of development of materials and their processing technologies for the period of up to 2030 [1, 2]:

- «intelligent» structures;
- fundamentally-oriented research, material qualification, nondestructive testing;
- computer methods of simulation of material structure and properties at their development and operation in a structure;
- intelligent, adaptive materials and coatings;
- materials with shape-memory effect;
- laminated metal-polymer, bimetal and hybrid materials;
- intermetallic materials;
- light, high-strength corrosion-resistant weldable alloys and steels, including those with high fracture toughness;
- single-crystal, heat-resistant superalloys, natural composites;
- energy-effective, resource saving and additive technologies of manufacturing parts, semi-finished products and structures;
- magnetic materials;
- metal-matrix and polymatrix composite materials;

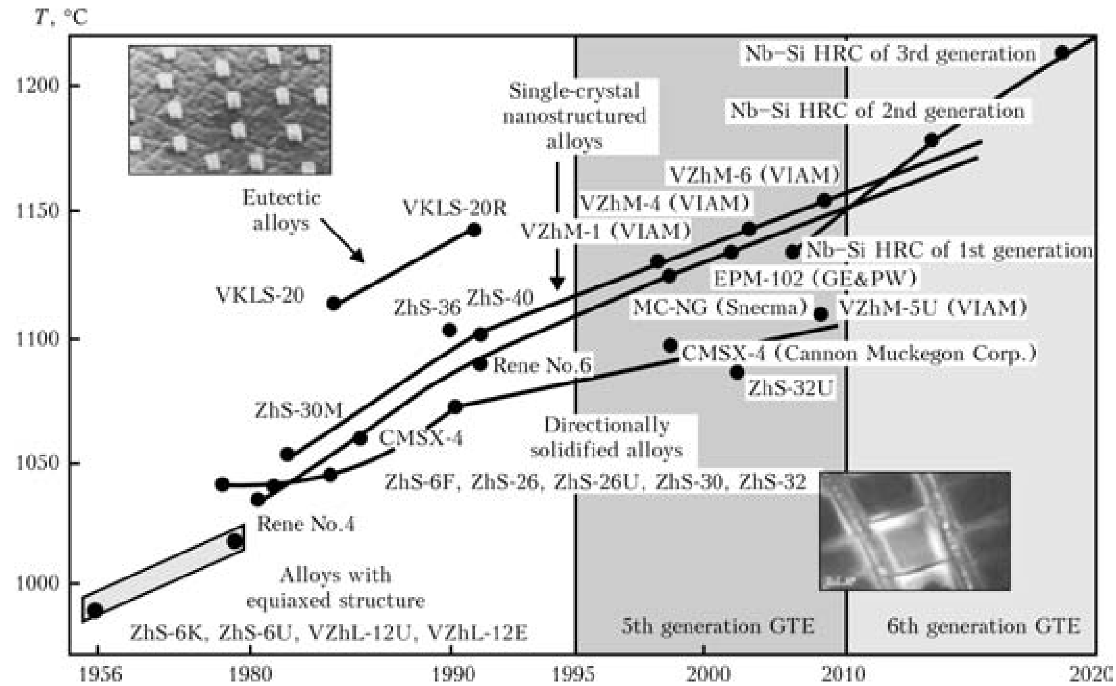


Figure 1. Dynamics of development of cast heat-resistant alloys

• polymer composite materials;

• high-temperature ceramic, heat-resistant and ceramic-like materials;

• nanostructured, amorphous materials and coatings;

• superlight foam materials;

• complex anticorrosion protection, strengthening, wear-resistant protective and heat-resistant coatings;

• climatic tests to ensure safety and protection from corrosion, ageing and biodamage of materials, structures and complex technical systems in natural environment.

Modern tendency in development of cast heat-resistant nickel alloys consists in application of deficit elements of VII and VIII group of D.I. Mendeleev periodic table, such as rhenium and ruthenium (Figure 1).

A special high-duty refractory ceramic shell mould operable up to the temperature of 1750 °C was developed for casting single-crystal GTE blades [3].

Modern heat-resistant nickel alloys (HRA) for GTE blade casting have reached working temperature limit of 1100–1150 °C, that is equal to 80–85 % of their melting temperature. Evolutionary development of heat-resistant nickel alloys led to creation of alloys of I, II, III, IV, and V generations, in which the melting temperature was increased through alloying by refractory elements such as tungsten, rhenium and ruthenium, reaching 1350–1370 °C. At present heat-resistant rhenium-ruthenium containing nickel alloy VZhM4 of the IV generation with long-term strength level of 120 MPa at 1150 °C on the base of 100 h is being introduced into production for manufacturing single-crystal blades [4, 5].

One of the promising directions of development of super heat-resistant alloys for blades exposed to temperatures above 1100 °C in operation, is development of natural composites, produced by the method of high-gradient directional solidification of complex-alloyed nickel-base eutectic alloys. Such developments resulted in creation of eutectic alloys with natural-composite structure of γ/γ'-MeC. To achieve 1250 °C working temperature of blades with natural-composite structure from HRA based on nickel eutectics, heat-resistant rhenium-ruthenium containing nickel alloys have to be used as matrix. It is intended to perform development of such eutectic alloys with increased content of rhenium and ruthenium by 2025 [2, 6].

To increase the temperatures of gas before entering the turbine, and, consequently, increase the engine efficiency, a new class of cast structural high-temperature sparsely-alloyed materials based on Ni_3Al intermetallics from VKNA series has been developed. These materials are designed for manufacturing gas-turbine engine parts operating in the temperature range of 900–1200 °C.

Intemetallic alloys feature low density (by 10–12 % lower than in heat-resistant nickel alloys), and high values of heat resistance at working temperatures. Application of light alloys based on nickel intermetallics as blades will allow lowering the load on turbine discs and increasing GTE resource 2.5–3.0 times.

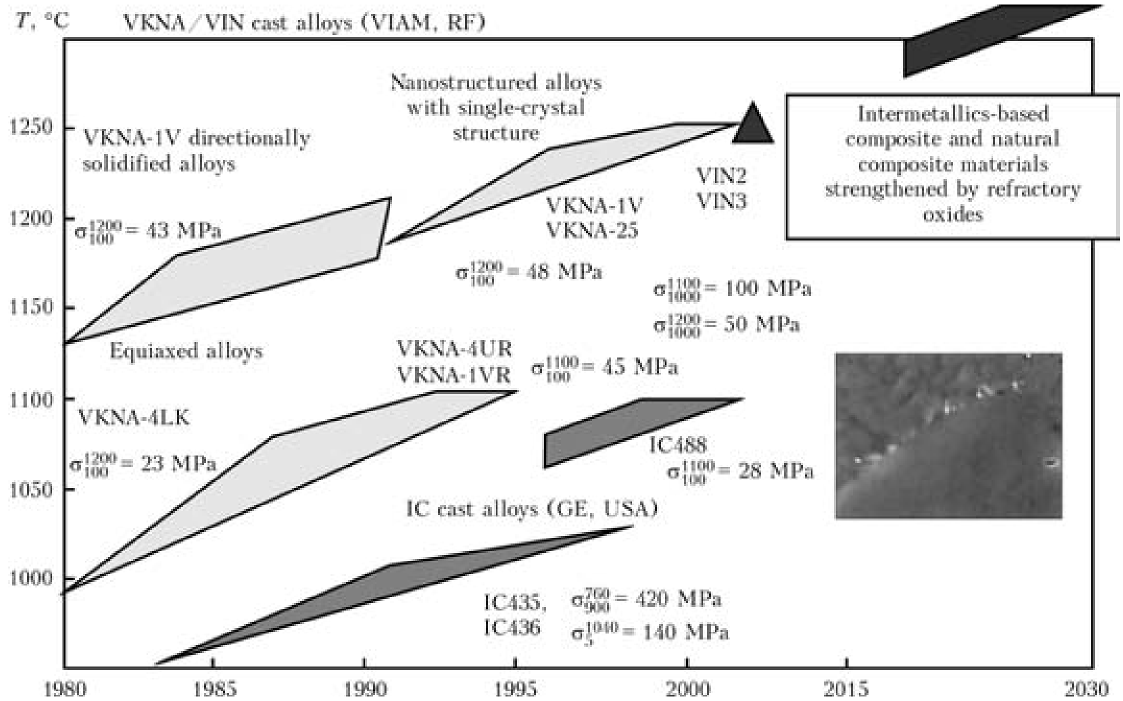


Figure 2. Development of nickel intermetallics based cast alloys

In keeping with their set of physico-mechanical properties, intermetallic alloys of VKNA grade are recommended for cast nozzle blades, parts of flue tubes, flaps and spacers of reactive nozzle with single-crystal structure for long-term operation at temperatures of 900–1200 °C. Alloys based on nickel intermetallics are applied in aeronautical engineering for the first time in the world (Figure 2) [7–9].

Development of new promising GTE is related to increase of working temperatures that requires creation of high-temperature alloys based on refractory matrices. In order to solve this problem, it is necessary to develop high-temperature processes of directional solidification using calculation-based methods of controlling variable temperature gradient, specialized high-temperature equipment and technologies of producing GTE parts from alloys based on refractory matrices.

FSUE «VIAM» set up a production area of up to 200 t/y capacity for production of modern super heat-resistant cast nickel alloys, including nanostructured alloys. The area includes modern vacuum induction furnaces: VIAM-2002 with up to 20 kg crucible, designed and manufactured by FSUE «VIAM» and VIM-50 and VIM-150 furnaces of «ALD Vacuum Technologies» (Germany) of 350 and 1000 kg capacity. Furnaces are fitted with computer control systems, allowing taking samples for chemical analysis of the produced metal during its melting and subsequent optimizing of its composition, as well as melt filtering during its pouring into steel pipes through hot ceramic foam filter. The above-listed features of melting equipment allow maintaining stable optimum composition of melted alloys, low level of impurities and gases, high purity by non-metallic inclusions, preservation of optimum quantity of microalloying additives that ensures producing nanostructured castings from them.

Monitoring of mechanical properties of the produced alloys, content of the main alloying elements, impurities and gases is performed in modern computerized equipment and at FSUE «VIAM» Testing Center (Figure 3).

Proceeding from the results of research work performed at VIAM in cooperation with Baikov IMET of RAS, a resource-saving technology of refining remelting of all kinds of wastes generated in metallurgical and casting production, has been developed and is applied in batch production. This technology allows producing alloys from 100 % wastes, which fully meet the requirements of currently valid specifications as to their purity, and are not inferior to alloys made from raw charge materials.

This technology allows development of a closed cycle for returning expensive and deficit alloying metals (rhenium, ruthenium, tantalum, cobalt, vanadium, etc.) to production. VIAM purchased and is now mounting a new vacuum induction furnace VIM-150 of «ALD» company (Germany) of the last generation with 1 t crucible capacity, the design of which according to VIAM's specification, incorporates modern con-

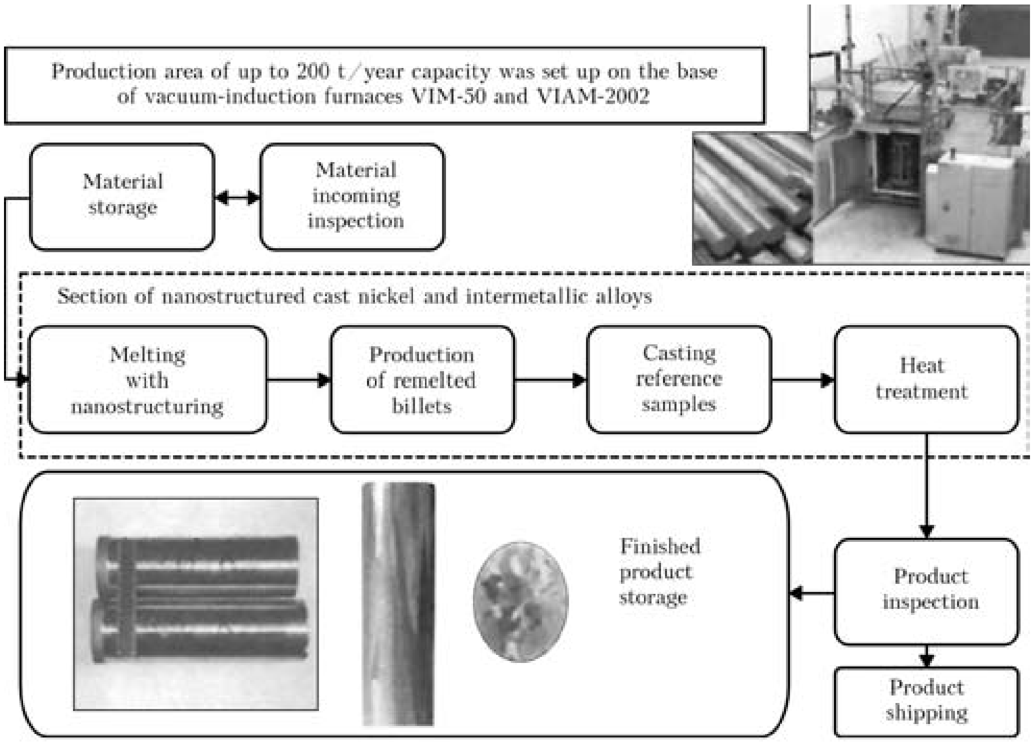


Figure 3. Production of heat-resistant cast alloys

trols and control systems, which allow additional improvement of deposited metal quality [10–13].

VIAM is technology developer and world's leading enterprise in the field of ion-plasma deposition of protective high-temperature, strengthening and thermal-barrier coatings on blades and other GTE and GTU parts. VIAM developed commercial automated equipment (MAP-type installations), in particular MAP-2 installation for gas ion-assisted deposition with ion energy of up to 40 kV (ion current density of up to 200 μA/cm^2), allowing modification of structural-phase state of condensates (coatings) through bombardment of the surface of growing condensate (coating) by accelerated gas ions (Ar, N_2) and, thus improving functional properties of the produced coatings. VIAM supplied to OJSC «Motor Sich» automated MAP-2 installation and a contract for supply of MAP-3 installation is being prepared now [14–19].

Technology supports deposition of all types of protective coatings (based on metals and alloys of various alloying systems, based on nitrides, carbides, oxycarbonitrides, nanolayered coatings from periodically alternating two to four layers of different materials of more than 15 μm total thickness, etc.), in particular, high-temperature gradient coatings of condensation-diffusion types (not having any analogs), and also allows conducting the processes of ion treatment of the surface in metal plasma (most recent process of ion beam surface modification, for instance, low-temperature (up to 600 °C) titanizing or titanizing-zirconating of a structural steel substrate) and processes of HRA strengthening (Figure 4).

For PD-14 engine FSUE «VIAM» developed high-temperature TBC bond coat of cementation + gas aluminizing + VSDP-3 (Ni–Cr–Al–Hf–Re–Y) + VSDP-16 + T/O type and together with OAO «PMZ» optimized the technology of deposition of a complex thermal-barrier coating with deposition of TBC ceramic layer by EB/PVD method on HPT blades in electron beam EB/PVD installation of «ALD» Company (Germany).

VIAM began development of new generation plasma-chemical equipment for deposition of protective and strengthening coatings from plasma gas flows, containing elements of the synthesized coating. Equipment will allow producing in a single-step process multilayer high-temperature TBC with barrier layers based on self-organizing nanocomposites for turbine blades from HRA based on refractory elements (niobium, molybdenum, chromium, tantalum), including eutectic composite materials based on niobium (or molybdenum, chromium) with intermetallic strengthening to working temperature of 1300–1500 °C, as well as functional strengthening single- and multilayer 2-D and 3-D nanostructured coatings with self-organizing ordered structure based on hard compounds of metals and alloys for GTE parts at up to 800 °C temperatures [14–19].

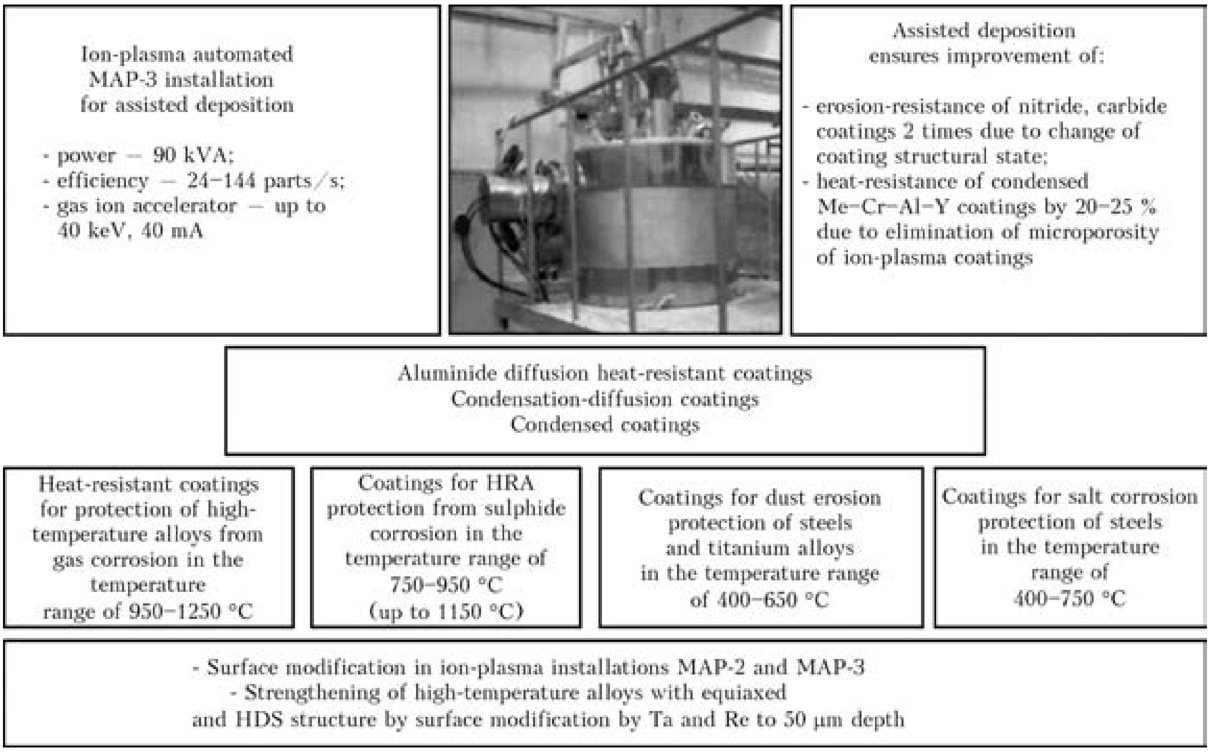


Figure 4. Ion-plasma protective and strengthening coatings

Special attention is given to development of the technology of producing finely-dispersed metal powders for various applications. These are powders of braze alloys and fillers for high-temperature vacuum diffusion brazing, including composite brazing, as well as powders of various alloys (on nickel, iron, titanium, aluminium and other bases) for additive technologies and powders of REM-based magnetic materials.

At present there is no batch production of such powders in the country. At FSUE «VIAM» the newest atomizer HERMIGA 10/100VI has been mounted and put into operation. It is designed for production of finely-dispersed metal powders based on nickel, iron and aluminium, and was the base to set up a production area for manufacturing of powder braze alloys and pilot batches of alloy powders for additive technologies. Powders are supplied to leading enterprises of the industry: JSC «Aviadvigatel», JSC «PMZ», JSC «Saturn», JSC «PDC «Teploobmennik», etc. [20].

Further progress in this direction is associated with development of technologies of producing active alloy powders of specified grain-size distribution, using crucibleless melting of consumable electrode.

Transition to powder manufacture by this technology will allow batch production of powders of local grades, based on titanium, nickel, niobium, etc., with their cost commensurable with those of foreign manufacturers, at wide range and volume of production of up to 30 t/m (Figure 5).

Braze alloys of VPr grades (Vpr1, Vpr2, Vpr4, Vpr7, Vpr16, Vpr28, Vpr24, VPr27, VPr36, Vpr42, VPr44, Vpr50, etc.), as well as technologies of brazing various materials with these braze alloys have been developed by VIAM and are widely applied in aircraft industry.

At present technologies of brazing, including diffusion brazing, developed at VIAM, became widely applied in manufacture of GTE parts and components.

Titanium-base intermetallic alloys are in greatest demand in the field of propulsion engineering. To achieve positive results in commercial production, the following technological tasks should be solved with success:

• development of alloys based on γ-phase of TiAl intermetallic with precision alloying system and density of 3.5–3.9 g/cm^3 and working temperature of up to 800 °C.

• development of technologies of melting intermetallic γ-alloy with ingot structure control;

• development of technologies of machining parts and blades (Figure 6).

Evolution of heat-resistant alloys for GTE discs, both local alloys and their foreign analogs is associated, primarily, with increase of working temperature and improvement of the set of mechanical properties, namely long-term and short-term strength, as well as fatigue characteristics (primarily LCF).

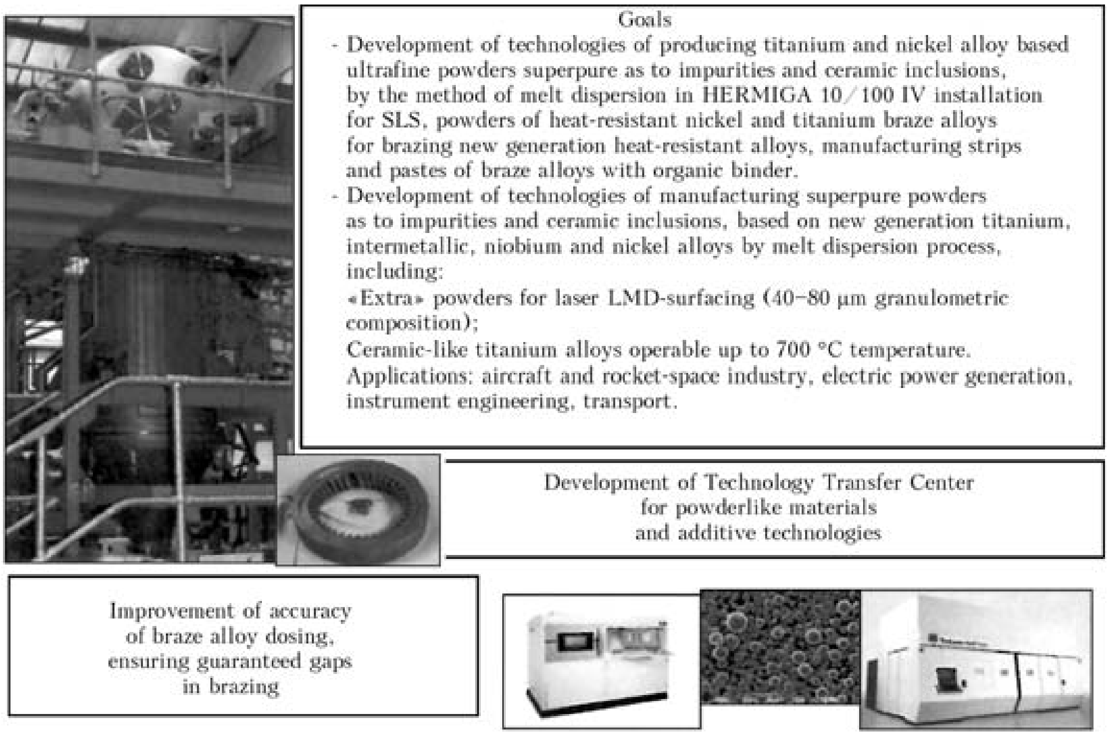


Figure 5. Development of atomization technologies to produce fine high-quality metal powders

FSUE «VIAM» specialists developed a new wrought heat-resistant alloy VZh175, which is characterized by a unique combination of mechanical properties, superior to the known local and foreign alloys as to short-term and long-term strength by up to 15 %, and as to low-cycle fatigue by up to 30 %, with maximum operating temperature of up to 800 °C. Such values have been achieved owing to balanced alloying, uniform fine-grained structure (15–30 μm grain) and original heat treatment mode, providing precipitation of strengthening phases of varying dispersity, including particles of less than 80 nm size.

Commercial production of large-sized stampings for discs (up to 550 mm diameter) from VZh175 alloy for fifth generation GTE has been mastered at OJSC «Electrostal» and OJSC «SMK» [21].

Further increase of service properties of nickel-base heat-resistant alloys through increase

γ-TiAl titanium intermetallic based cast alloys

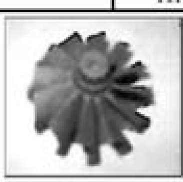
Alloy	Semi-finished product	σ_t, MPa	$\sigma_{0.2}$, MPa	E, GPa
Experimental VIT-Kh	Casting 25 mm HT	≥554	≥538	169
VTI-3L	Casting 25 mm HIP + HT	≥545	≥535	168

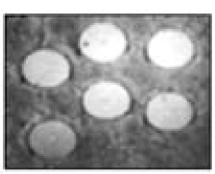
Produced by: FSUE «VIAM»

Titanium intermetallic based wrought alloys

Alloy	Semi-finished product	σ_y, MPa	$\sigma_{0.2}$, MPa	δ, %
VTI-4	Sheet 2.5 mm	≥1150	≥1100	6
VIT1	Rod 25 mm dia.	≥1300	≥1150	8

Produced by: JSC «VSMPO-AVISMA» Corporation





TiAl based blades and wheels of turbocompressors

CM advantages
(compared to traditional alloys):
- 40 % lower density;
- 1.5 times higher ultimate strength;
- 2 times higher high temperature strength

Applications:
- aircraft industry;
- transport engineering

CM application will provide:
- 40 % lower component weight;
- 250 °C higher working temperatures;
- increased fire safety up to 900 °C.

Figure 6. Promising titanium-intermetallics based materials

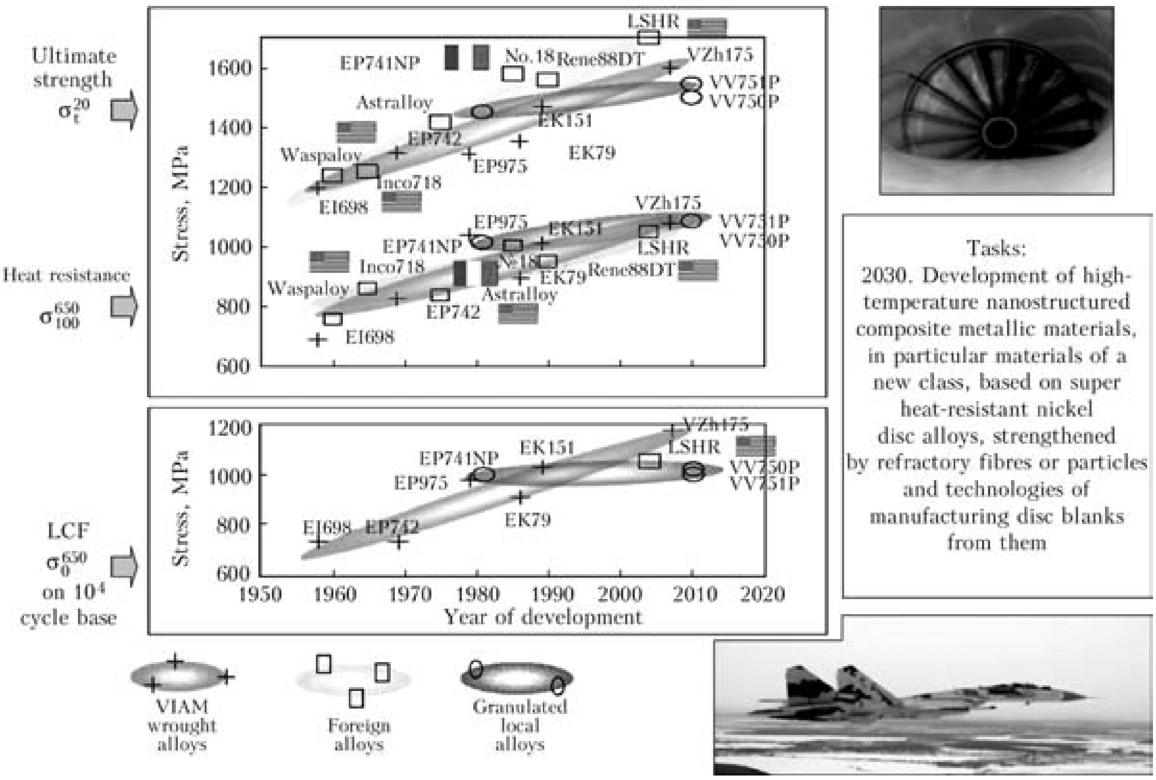


Figure 7. Development of heat-resistant nickel alloys for GTE discs

of srengthening refractory and γ′-forming element content is highly problematic, as today already the alloying level of these alloys has reached a critical value. Therefore, the main directions of development of GTE disc materials involve creation of new nanostructured composite materials, in particular those based on super heat-resistant wrought nickel alloys, strengthened by refractory fibres or particles (Figure 7).

High-strength weldable alloy VZh172, owing to balanced alloying and optimal content of strengthening phase, is superior, in terms of strength and heat resistance values, to currently available local and foreign alloys for similar purposes by 15–70 % with preservation of weldability and technological ductility values high for this material class.

VZh 172 alloy is designed for application as material for casing of combustion chamber and turbine and other heavy-duty parts and components of GTE hot circuit stator, operating at up to 900 °C temperature. In addition, VZh172 alloy can be applied as material for discs of HPC welded rotor and HPC rolled blades with operating temperature of up to 750 °C.

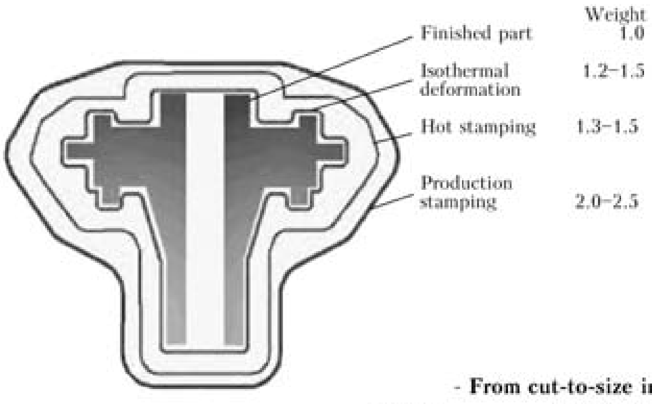
Technological parameters have been determined for argon-arc welding of new super heat-resistant plate nickel alloy VZh171, strengthened by chemicothermal treatment (internal nitriding) and designed for manufacturing welded parts and components of combustion chambers, their highest-temperature resistant elements and other parts of future GTE. Nitrides feature higher thermodynamic stability than intermetallics and carbides, allowing working temperature to be increased up to 1200–1250 °C. Welding of VZh171 alloy with nitriding after welding with application of base material in the form of filler, allows producing welded joints with high hot cracking resistance ($A_{cr} \geq 4.5$ mm/min), with strength close to that of base material ($\sigma_{w.j} = 0.95$–$1.0\sigma_{b.m}$) [22].

FSUE «VIAM» developed and realized an innovative technology of isothermal stamping in air to produce low-cost high-quality disc blanks from super heat-resistant nickel alloys for small-sized GTE.

New energy-effective and resource-saving technology features a high coefficient of material utilization (its values are 2–3 times higher compared to stamping in open dies, used in large industrial enterprises), better processing of metal structure, thus ensuring high stability of mechanical properties.

Both batch-produced extruded rods of 80–150 mm diameter and cut-to-length ingots produced by the process of high-gradient directional solidification (HGDS) can be used as initial billet for isothermal stamping.

Compared to foreign developments, high-temperature isothermal stamping is performed in air, and not in low-efficient vacuum units of complex



Effectiveness:
- 1.5–2.0 increase of CMU through reduction of allowances and optimization of form change in stamping transitions;
- 20–30 % reduction of labour consumption in machining;
- lowering of power consumption due to reduction of technological processing operations and use of lower power equipment;
- reduction or elimination of operations of intermediate removal of surface defects in production of stampings from difficult-to-deform super heat-resistant and high alloys.

FSUE «VIAM» organized batch production of disc stampings for small-sized GTE

Production volume: up to 1500 pcs/year

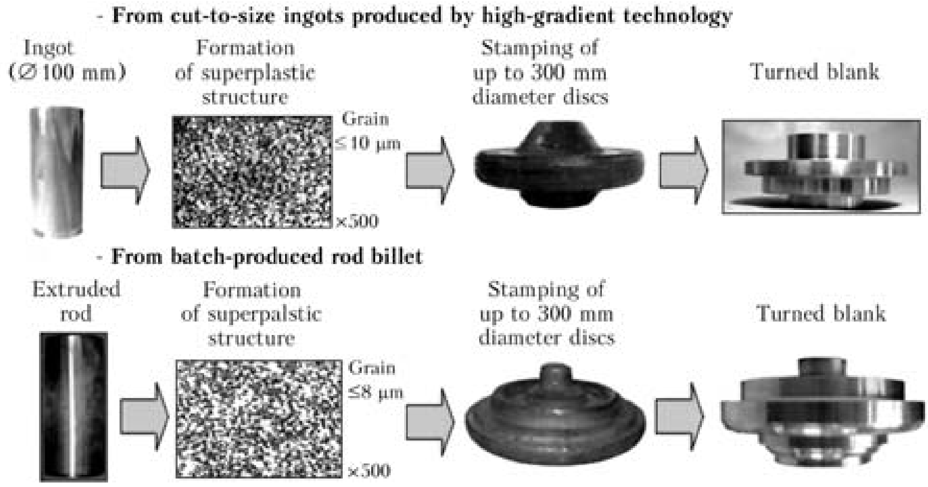
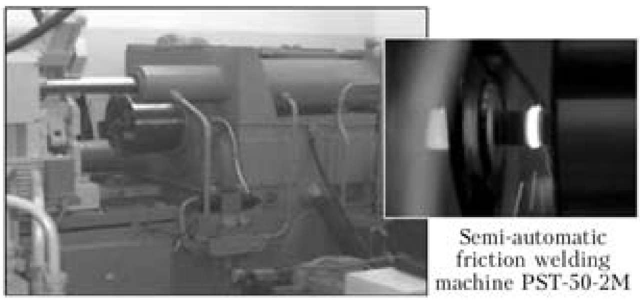


Figure 8. Isothermal stamping of heat-resistant disc alloys in air for small-sized GTE

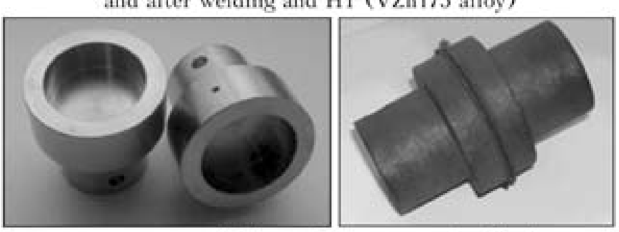


Semi-automatic friction welding machine PST-50-2M

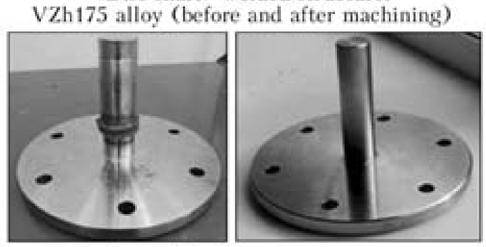
Rotational friction welding provides:

- possibility of welding parts from materials difficult-to-weld by fusion welding;
- producing welded joints with strength close to base material strength;
- increasing the effectiveness of welded component manufacturing;
- considerable lowering of manufacturing labour consumption;
- possibility of welding process automation.

«Tube-to-tube» welded joint before and after welding and HT (VZh175 alloy)



«Disc-shaft» welded structure. VZh175 alloy (before and after machining)



Mechanical properties of welded joints of heat-resistant wrought nickel alloys

Welded materials	Technology variant	σ_t^{-20}, MPa	σ_t^{650}, MPa	σ_{100}^{750}, MPa	σ_t^{750}, MPa	KCU^{-20}, kJ/m²	$K = \sigma_{w.j}/\sigma_{b.m}$
VZh175 + VZh175	Quenching + ageing + welding	1232	1295	638	–	295	≥0.8
	Quenching + welding + ageing	1550	1500	940	–	220	0.90–1.0
	Welding + quenching + ageing	1560	1510	850	–	280	0.85–1.0
EI698 + EI698	Welding + quenching + ageing	1120	–	–	770	400	≥0.9
EP975 + EP975	Welding + quenching + ageing	1120	–	–	990	360	≥0.9
VZh172 + EK79	Welding + quenching + ageing	1300	–	–	850	380	≥0.8–0.95

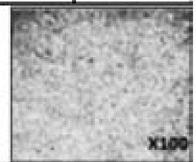
Figure 9. Development of technologies of rotational friction welding

For power parts of engines (shafts, fasteners)
(steel working temperature of up to 450 °C)

Alloy	σ_t	$\sigma_{0.2}$	σ_t	$\sigma_{0.2}$	σ^{400}_{100}	$\sigma^{400}_{0.2/100}$
	MPa (20 °C)		MPa (at 400 °C)			
VKS-170	1570	1520	1300	1200	1000	800
VKS-180	1720	1600	1400	1350	1000	825
EP517 (batch-produced)	1100	950	850	800	880	490
Maraging 250 (USA)	1725	1690	1523	1447	ND	ND

Engine part weight lowering by up to 30 % is ensured

Fine-grained structure of steel after strengthening heat-treatment of semi-finished products



Application: LPT shaft of PD-14 engine of JSC «Aviadvigatel» (steel VKS-170TU 14-1-4479–88; forging code number «6-33» TU 1-80121-5421–2009)

Quality control

Produced by: OJSC «MZ «Elektrostal», OJSC «SMK»

Figure 10. Mechanical properties of high-strength maraging steels

design with expensive molybdenum dies (Figure 8).

FSUE «VIAM» will set up a Center for transfer of technologies of isothermal deformation in air of new generation heterophase difficult-to-deform HRA [23, 24]. Technologies of rotational friction welding of heat-resistant wrought nickel alloys in similar and dissimilar combinations have been developed for manufacture of items of «disc-shaft», «blisc», «bling» type, providing welded joints with the strength of 0.8–0.9 of the less strong alloy ($K = \sigma_{w.j}/\sigma_{b.m}$). Main parameters of the process of alloy friction welding have been selected. Dependence of friction welding modes and welded joint mechanical properties on heat treatment of welded items was studied. Friction welding of a disc model from VZh175 alloy of up to 300 mm diameter and shaft model of 35 mm diameter was performed (Figure 9).

FSUE «VIAM» developed high-strength structural maraging extra low-carbon steels of 18Ni–8Co–5Mo–Ti alloying system: VKS-170 ($\sigma_t \geq 1570$ MPa) and VKS-180 ($\sigma_t \geq 1720$ MPa), recommended for operation up to 400–450 °C.

Table (Figure 10) gives mechanical properties of VKS-180 and VKS-170 steels compared to EP517 steel used in batch production and foreign analog — Maraging 250. Data given in the Table show that structural maraging steels VKS-180 and VKS-170 are superior to EP517 steel as to strength properties up to +400 °C, and are not inferior to foreign analogs as to the respective characteristics. These steels are also superior to currently applied ones in terms of fatigue life, fatigue resistance, long-term strength and creep.

High-strength structural maraging steels VKS-180 and VKS-170 will be used for GTE shafts to lower the shaft mass by approximately 30 % compared to applied martensitic steels (Figure 10).

Over the period of 2010–2012 VIAM developed the composition of heat-resistant VKS241 steel for GTE bearings and helicopter gears; technology of melting, hot plastic forming and strengthening heat treatment, providing not less than *HRC* 60 hardness at 20 °C, heat resistance of 500 °C, adaptability to fabrication and structural homogeneity.

By the level of properties (impact toughness, hardness) VKS241-VI steel is on the level of its analog — M50 (USA) and is approximately 2 times superior to currently applied EI347 steel as to impact toughness.

New heat-resistant bearing steel VKS241 is 1.5 times less expensive than EI347 as to alloying element cost.

In conclusion it should be noted that application of new materials developed at FSUE «VIAM» will allow solving important scientific-technical tasks, namely developing GTE with power-to-weight ratio of 20:1, increasing gas working temperature to 2000 K, extending GTE service life by 1.5–1.7 times, thus ensuring fast advance of aircraft engine construction industry.

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Received 18.04.2013

GENERALIZED ADDITIVE MANUFACTURING BASED ON WELDING/JOINING TECHNOLOGIES

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Being in the leading position of non-conventional welding technologies R&D in China, Beijing Aeronautical Manufacturing Technology Research Institute (BAMTRI) has been involved in a number of research programs relating to generalized additive manufacturing based on welding/joining technologies. Such research programs and projects provide aviation industry a rapid response in design and trial manufacture of new products. BAMTRI, founded in 1957, is a comprehensive research institute specializing in the research of advanced aeronautical manufacturing technologies and development of related equipment as well as promoting such technologies and equipment to industrial applications. Based on its superiority in electron beam, laser beam, plasma & ion beam processing technologies, the National Key Laboratory for Power Beam Processes was established at BAMTRI in 1993. Power beam welding/joining/processing and solid state welding/joining are the two most important R and D areas at BAMTRI to solve the «unique» and «critical» problems in modern aeronautical manufacturing as well as to establish the technical basis for generalized additive manufacturing, providing frontier technologies and related machinery to aviation enterprises in China. 10 Figures.

Keywords: *survey, non-conventional welding technologies, power beam welding, additive manufacturing, aviation industry, application*

Non-conventional welding/joining technologies at BAMTRI. To meet the increasingly growing demands of the aviation industry to develop new aircrafts and aero-engines from generation to generation, continuous efforts have been made to exploit advanced welding/joining technologies. New methods and related equipments have been developed for precise and automatic material processing and structural elements forming. For the past half century, a system of non-conventional welding/joining technologies for aeronautical manufacturing has been formed at BAMTRI, which could be outlined as follows.

System of non-conventional welding/joining technologies for aeronautical manufacturing

- I Integrity of welded structures and control of stres and distortion
- II Gas shielded arc welding
- III Brazing and transient liquid phase joining (TLP)
- IV Resistance welding
- IV Power beam welding/joining/processes
  - ▲ IV-1 Electron Beam
  - ▲ IV-2 Laser Beam
  - ▲ IV-3 Plasma and Ion Beam
- V Solid state welding/joining
  - ▲ V-1 Diffusion bonding (DB) and TLP
  - ▲ V-2 Super plastic forming/diffusion bonding (SPF/DB)
  - ▲ V-3 Friction welding (FW)
    - ■ V-3-1 Inertia FW
    - ■ V-3-2 Linear FW
    - ■ V-3-3 Friction stir welding (FSW)

Among the non-conventional welding/joining technologies in this system, power beam welding/joining/processing and solid state welding/joining, as mentioned above and will be described below, are the two most important R and D areas at BAMTRI, providing tools to solve the «unique» and «critical» problems in modern aeronautical manufacturing, which are also potentially attractive and exciting for designers together with engineers to provide more creative thought and space for innovatory implementation of new products.

Power beam welding/joining/processes. Electron beam (EB) R&D activities at BAMTRI mainly involve deep penetration welding, additive manufacturing, electron beam physical vapor deposition for thermal barrier coatings (TBCs), electron beam texturing, electron beam brazing and other material processing. One of EB ma-

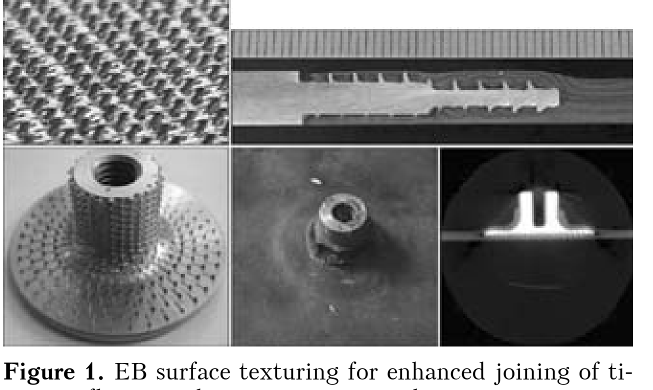

Figure 1. EB surface texturing for enhanced joining of titanium flange with composite material

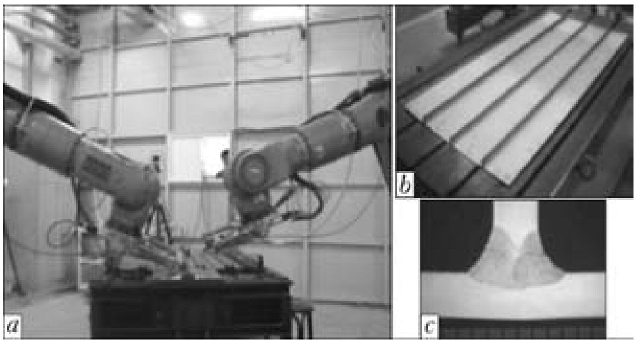

Figure 2. Dual-beam laser robotic system for welding of aluminum and titanium airframe (*a*), stiffened panels with (*b*) T-joint simultaneously from both sides of fillet welds (*c*)

chine of 150 kV, 60 kW, 85 m^3 (7.5 × 3.8 × 3 m) was built for deep penetration welding of titanium components with the thickness up to 150 mm.

The superiority of electron beam with extremely flexible scanning ability has been applied for surface texturing to obtain enhanced joining of titanium flange with polymer composite, as shown in Figure 1.

Laser Beam R&D activities at BAMTRI mainly involve welding, cutting, drilling, peening, additive manufacturing as well as hybrid laser/MIG welding, texturing and surfacing. Figure 2 illustrates an experimental set-up of dual-beam laser robotic system (Figure 2, *a*) for welding of aluminum and titanium airframe stiffened panels (Figure 2, *b*) with T-joint (Figure 2, *c*) welded simultaneously from both sides of fillet welds.

Figure 3, *a* shows an application of precise laser drilling technologies for aero-engine turbine blades. To improve fatigue life, laser peening technology is also performed on compressor blades (Figure 3, *b*).

Plasma and ion beam R&D activities at BAMTRI mainly involve plasma spraying for turbine blades with TBCs as well as nano-structured TBCs, plasma immersion ion implantation and deposition, such as TiN deposition, thin film and TiCrN multilayer film deposition on aero-engine parts.

Solid state welding/joining technologies. As mentioned above, the importance and contribution of solid state welding/joining technologies for aeronautical manufacturing are incomparable in solving specific «unique» and «critical» problems; in solid state welding/joining technologies there are no troubles and imperfections being inherent in fusion welding processes.

In the early 1980's, super plastic forming/diffusion bonding (SPF/DB) technology was firstly developed at BAMTRI for fabricating airframe titanium panels in order to reduce weight and improve structural performance. Nowadays multi-layered inner-stiffened titanium panels with complex configurations have been fabricated to meet specific requirements from aviation industry, space sector and other fields. Technical and economic benefits brought by SPF/DB are of great value for both designers and fabricators.

Linear friction welding (LFW) is an unique technique to manufacture high performance aero-engine blisks so as to replace the traditional tenon joints, achieving the weight reduction for the entire structure. Figure 4 shows a part of the as-welded blisk and macro structure of the solid

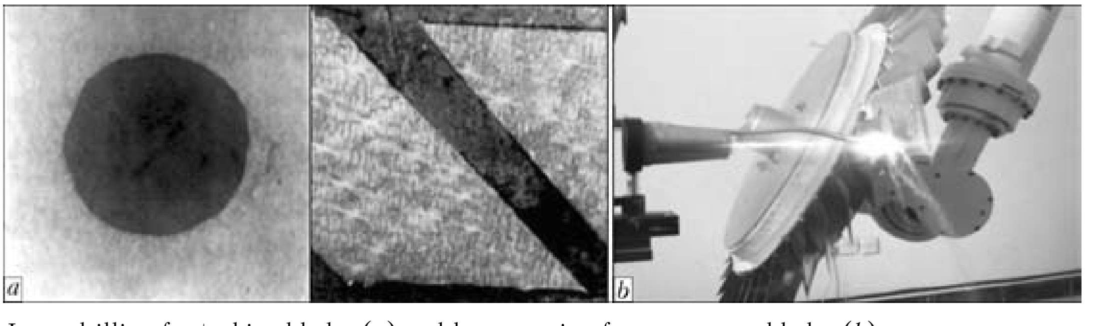

Figure 3. Laser drilling for turbine blades (*a*) and laser peening for compressor blades (*b*)

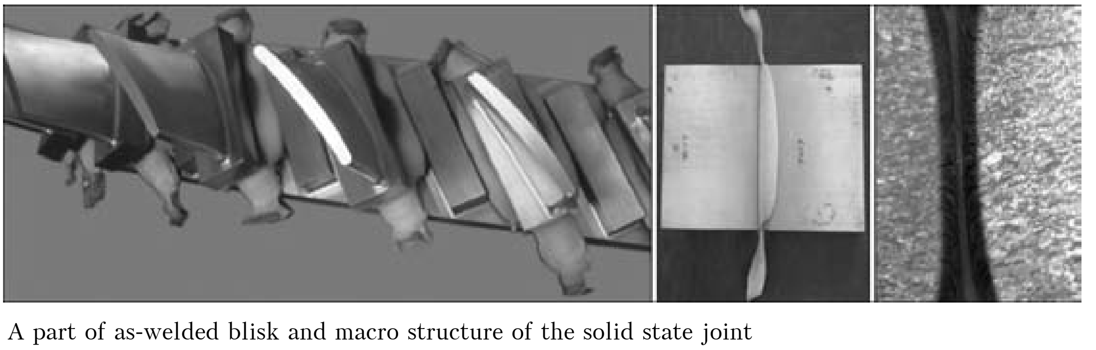

Figure 4. A part of as-welded blisk and macro structure of the solid state joint

state joint. LFW can be considered as a block joining process in solid state additive manufacturing that will be described below.

Moreover, friction stir welding (FSW), which is also a solid state welding process, has been developed at BAMTRI for over fifteen years, and this development is ongoing. As a great alternative choice, FSW has attracted more attentions to be used instead of the traditional fusion welding in the area of aluminum structure joining. Similar to the LFW, FSW is also a powerful block joining process in solid state additive manufacturing.

Understanding of generalized additive manufacturing. Additive manufacturing is different from the traditional material removal machining/cutting reduction manufacturing. In additive manufacturing, structural elements are formed usually by metal melting deposition. Such deposition is generally performed layer-by-layer with CAD/CAM techniques which is based on wire/powder feeding and melting using electron beam or laser beam. In generalized additive manufacturing, structural elements could also be produced by block joining using allied energy sources for welding/joining technologies, such as mechanical friction heating etc.

The disadvantages of traditional material removal machining/cutting reduction manufacturing techniques include low effectiveness, high material cost, and relatively long manufacturing cycle while a great portion of valuable material is turned into undesirable metal chips.

Compared with traditional techniques, additive manufacturing has many advantages and benefits, such as free forming, near net shape fabrication, material and time saving, flexibility and ability in controlling and optimizing performances of products.

Besides laser beam and electron beam, other allied energy sources are also applicable for generalized additive manufacturing, such as: chemical, electro-chemical, mechanical etc., especially pile-up forming could be performed applying block joining to produce directly integrated monolithic metallic structural elements.

From a welding researcher' s point of view the original formation of generalized additive manufacturing is buildup cladding by manual metal arc welding, or using gas tungsten arc welding as well as micro-plasma welding with wire feeding for surfacing and repair work. Although these heat sources do not possess the suitable flexibility and advantages as electron beam and laser beam used for modern additive manufacturing, all the heat sources for fusion welding are applicable for additive manufacturing, provided computer aided automation is entrusted to them. Besides, block joining processes using mechanical friction heating like linear friction welding are also considered as the solid-state additive manufacturing.

For the past two decades, the technical basis for rapid development of additive manufacturing has been attributed to the extreme flexibility of power beams like electron beam and laser beam (such as power control, focusing control, deflection capability, scanning control, long focused active zone) combined with CAD/CAM technologies. At the same time, additive manufacturing has been more and more applied for direct metal free forming fabrication.

In general, modern advanced generalized additive manufacturing could be classified into three categories: 1) direct metal free forming fabrication; 2) non-metallic parts direct manufacturing; 3) rapid bio-model direct forming.

Figure 5 shows the distinctions between additive manufacturing in a narrow sense (inner circle) and additive manufacturing in a broad sense (outer ellipse). The inner circle represents the additive manufacturing in a narrow sense

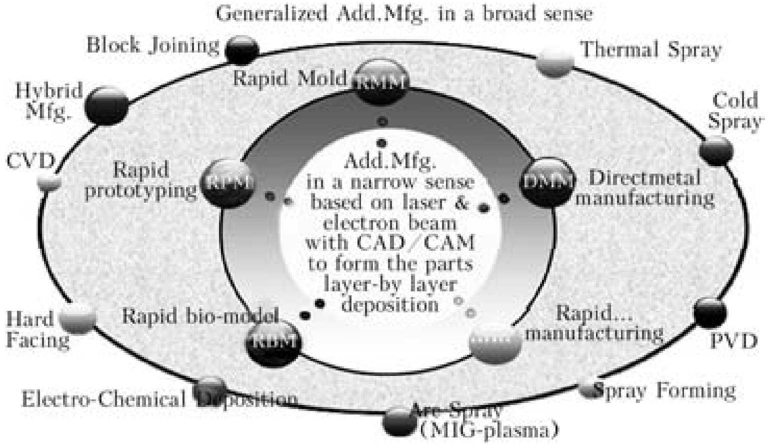

Figure 5. Distinctions between Add. Mfg. in a narrow sense (inner circle) and Add. Mfg. in a broad sense as generalized Add. Mfg. (outer ellipse)

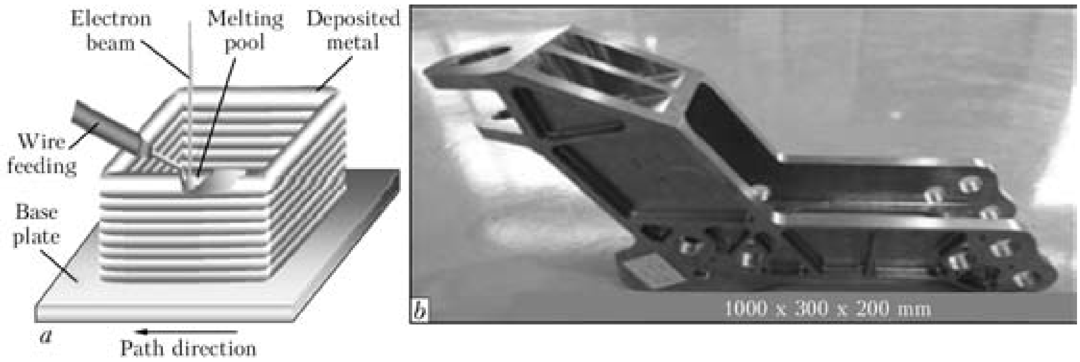

Figure 6. Principle of (*a*) Add. Mfg. based on EB with wire feeding and (*b*) deposited titanium structural element after machining

based on laser and electron beams with CAD/CAM to form the parts by deposition layer-by-layer. The outer ellipse gives an idea to understand the generalized additive manufacturing based on allied energy sources such as electrical arc and plasma for melting deposition, light sources for photo curing stereo-lithography, electro-chemical sources for deposition in liquid phase, and mechanical friction heating sources for block joining etc.

It should be stressed that in past years the enthusiasm to promote 3D printing is mostly related to non-metallic part direct fabrication. But nowadays direct metal free forming manufacturing is expected to be the follow-up upsurge of additive manufacturing to change gradually the traditional manufacturing mode from mass production to customized product made to order. Another breakthrough in bio-model direct forming as generalized additive manufacturing is predictable in the near future.

Potential application of generalized additive manufacturing. *Additive manufacturing based on electron beam.* Figure 6 shows the principle of additive manufacturing process based on electron beam with wire feeding. In vacuum chamber the wire fed to welding pool is melted by CAD controlled focused scanning electron beam, layer-by-layer deposition path is directed according to the CAD model (Figure 6, *a*); a typical deposited titanium structural element after machining of 1000 × 300 × 200 mm is also shown in Figure 6, *b*.

In the past few years, EB additive manufacturing titanium alloy wire composition system made to custom-order has been developed at BAMTRI to meet the required properties and structural performance. Technologies for deposition path control, parameter optimization, as well as post treatment are utilized to avoid possible emergence of imperfections and distortion. In general, mechanical properties of the deposited elements are compatible with forged parts.

Up to now the largest-sized facility for electron beam additive manufacturing with wire feeding system has been set up at BAMTRI. It is capable to fabricate structural elements with dimensions of 1500/800/3000 mm.

Additive manufacturing based on selective powder melting using electron beam is also implemented in a vacuum chamber. Metal powder spread on the powder bed is melted layer-by-layer by scanning electron beam following the CAD model paths.

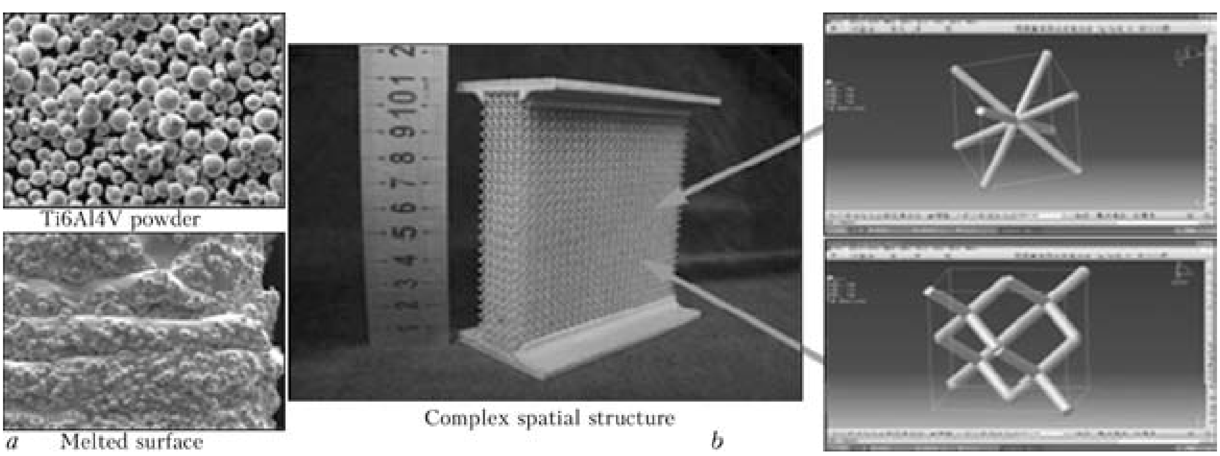

Figure 7. Add. Mfg. based on selective powder melting using EB: *a* — Ti6Al4V powder and melted surface; *b* — built-up complex spatial structure

In Figure 7 Ti6Al4V powder and melted deposition surface are shown (Figure 7, *a*); in this way complex spatial structure (Figure 7, *b*) can be built-up easily.

Additive manufacturing based on laser beam. Using laser beam, additive manufacturing could be implemented based on either direct laser melting deposition with coaxial feeding powder or selective laser melting with spread powder on bed layer-by-layer. Besides, laser beam additive manufacturing based on wire feeding is also explored at BAMTRI.

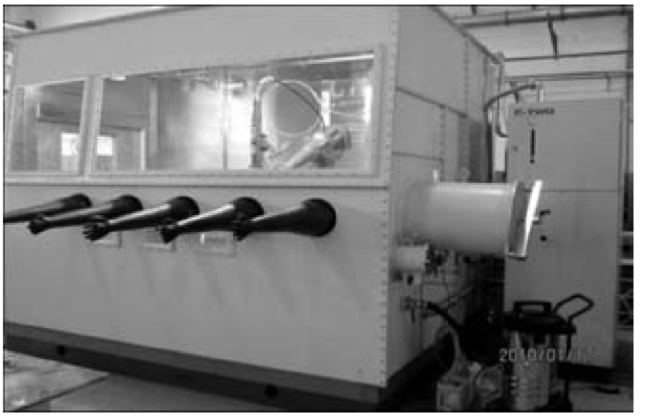

Figure 8. Universal laser beam additive manufacturing robot facility at BAMTRI for direct laser melting, selective laser melting as well as wire feeding laser melting

Figure 8 shows the universal laser beam additive manufacturing robot facility at BAMTRI for direct laser deposition melting, selective laser melting deposition as well as wire feeding laser melting deposition (chamber with dimension of 3 × 3 × 2.5 m).

Technological procedures for laser beam additive manufacturing almost the same as for electron beam additive manufacturing. Material system with either wire or powder composition preparation made to custom-order also has been developed to meet the required properties and structural performance.

For more precise deposition forming (e.g. surface roughness Ra: 10 ~ 30 μm), high performance laser beam, fine granulated powder layer thickness should be matched. Subsequently, it is undoubtedly logical that the as deposited parts will be the final products or just finished surface polishing is needed.

Generalized additive manufacturing based on block joining. For high performance aero-engine, the compressor weight reduction can be reached up to 50 % if the traditional tenon joining of blades to disk can be replaced by blisk (blades to be welded to disk). Solid state additive manufacturing based on block joining by linear friction welding to produce integrated monolithic welded blisk is an effective tool for achieving the above mentioned idea.

Figure 9 exhibits the weight reduction for aero-engine tenon joining replaced by welded integrated monolithic blisk (Figure 9, *a*) using linear friction welding (Figure 9, *b*) as solid state additive manufacturing.

Low effectiveness in material saving and time saving of traditional material removal reduction manufacturing based on machining & cutting is fully reflected on monolithic stiffened airframe panel fabrication. Nowadays friction stir welding (FSW) turns the tide and brings about a radical change in the situation of block joining additive manufacturing of aluminum monolithic stiffened airframe panels. Stiffening ribs are assembled and welded to skin sheets using FSW for aluminum monolithic stiffened airframe panel fabrication. The name of solid state block joining additive manufacturing by FSW matches the reality.

In the case of titanium alloy, monolithic stiffened airframe panel fabrication can be achieved

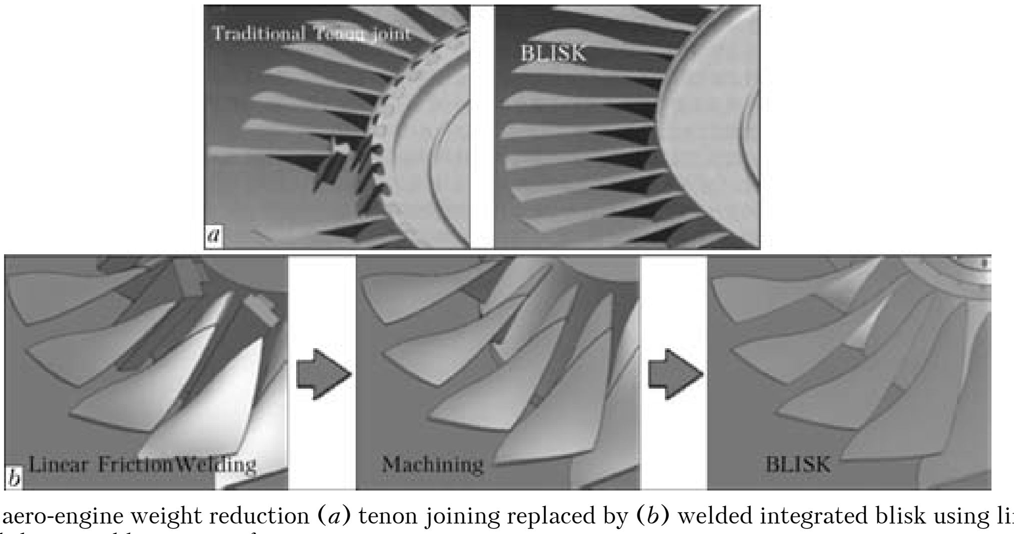

Figure 9. For aero-engine weight reduction (*a*) tenon joining replaced by (*b*) welded integrated blisk using linear friction welding as solid state additive manufacturing

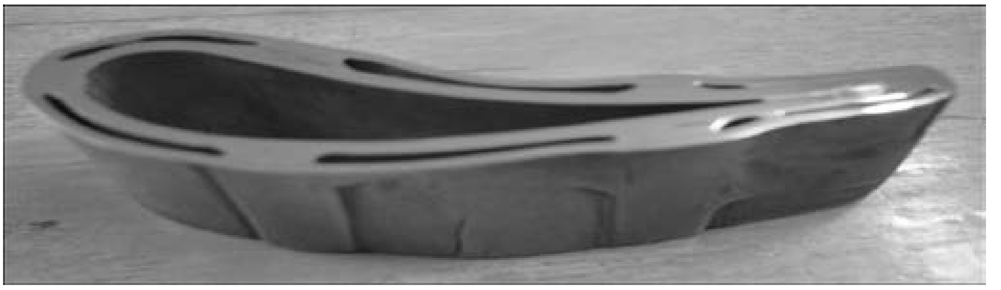

Figure 10. Turbine blade with complicated inner cooling gas channeling to be fabricated by additive manufacturing using electron beam physical vapor deposition (EB-PVD)

by block joining additive manufacturing using laser welding; titanium stiffening ribs are assembled and welded to titanium skin sheets using dual-beam laser robotic system as already shown in Figure 2.

Generalized additive manufacturing based on other energy sources. The variations of generalized additive manufacturing based on other applicable allied energy sources have been shown above in Figure 5.

As a typical application shown in Figure 10, an example is given to electron beam physical vapor deposition (EB-PVD) for additive manufacturing of turbine blade with complicated inner cooling gas channeling.

Technology and material composition of the blades made to custom-order for electron beam physical vapor deposition (EB-PVD) are selected to match the required properties and structural performance. In the vacuum chamber either a single electron beam gun or multiple electron beam guns can be used to form the blades by depositing different materials. It is expected that EB-PVD will be full of promise in additive manufacturing of newly designed aero-engine parts.

Conclusions

1. In terms of market pull there is very strong interest in additive manufacturing (particularly using power beams: electron beam & laser beam) from the aviation industry, especially for airframe and aero-engine applications as strategically important. BAMTRI has been involved in a number of research programs for aviation companies to provide a rapid response in design and trail manufacturing of new products.

2. For generalized additive manufacturing other allied energy sources are also applicable such as electrical, chemical, electro-chemical, mechanical etc. Especially pile-up forming could also be performed applying block joining (e.g. friction welding) to produce directly integrated monolithic metallic structural elements including aero-engine blisks and airframe stiffened panels.

3. Generalized additive manufacturing based on block joining (particularly friction welding) offer the potential for solid-state joining to build up near net shape elements by assembling of relatively simple parts. BAMTRI has been developing this solid state additive manufacturing technology for aero-engine parts as well as for airframe stiffened panels fabrication, demonstrating high value applications in other industry sectors.

Received 21.02.2013

WELDING OR ADHESIVE BONDING — IS THIS A QUESTION FOR THE FUTURE?

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Modern light-weight structures are composed of most different materials. The joining of these materials with and among one another requires the application of different joining techniques with the focus on welding and adhesive bonding. In this paper, the advantages of both methods are discussed and possibilities for the combined application of welding and bonding techniques are presented. 5 Figures.

Keywords: *laser beam welding, plasma soldering, friction stir welding, adhesive bonding, steels, aluminium alloys, automotive car body, advantages of methods*

The joining technology is an interdisciplinary technology which allows the combination of parts which have most different geometries and which are consisting of a wide variety of materials towards complex structures and products.

Riveting has been the dominating joining technology of the 19th century. Numerous impressive structures serve as demonstration, for example, the Eiffel tower with more than 2.5 mln rivets. In the course of the 20th century, riveted structures were increasingly replaced by welded structures. The production of welded structures is, on the one hand, economically more efficient and the structures have, on the other hand, a higher strength. Besides welding, the adhesive bonding technology is, nowadays, increasingly used for many applications.

A major advantage of welding compared with adhesive bonding is its advance of several decades in research and industrial application. The welding technology is for many joining tasks still the called-for method.

Particularly for thick-walled welded structures which are joined on butt joint, T-joint or cruciform joint, the application of the welding technique is unrivalled. In this field, also methods which are assumed to be out-of-date, such as electro-slag welding, can be applied with a high efficiency. Figure 1 depicts an impressive example.

For the manufacturing of a large press, a steel sheet structure has been chosen instead of a cast structure. The steel sheet structure was manufactured with particularly lesser quantities of material and was, thus, much more cost-favourable. However, this type of structure required to join the large-format steel plates with one another. Each plate had a thickness of several centimetres. As a standard welding technology for this task, multiple-pass submerged arc welding has been applied with a production duration of three up to four weeks just for the weld. The application of electro-slag welding allowed a reduction of the welding time down to 14 h, compare Figure 1.

In working with modern designs it is often not possible to apply just one welding method. They are often characterized by the use of many different materials such as different steel grades,

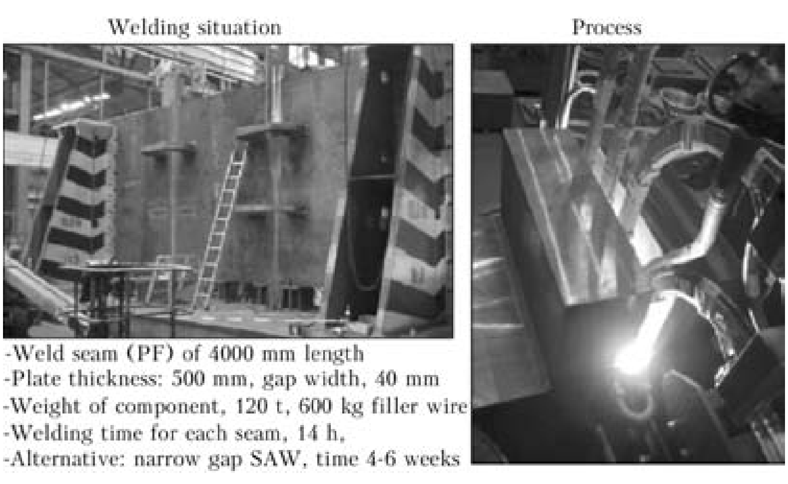

Figure 1. Electro slag welding of large components for presses

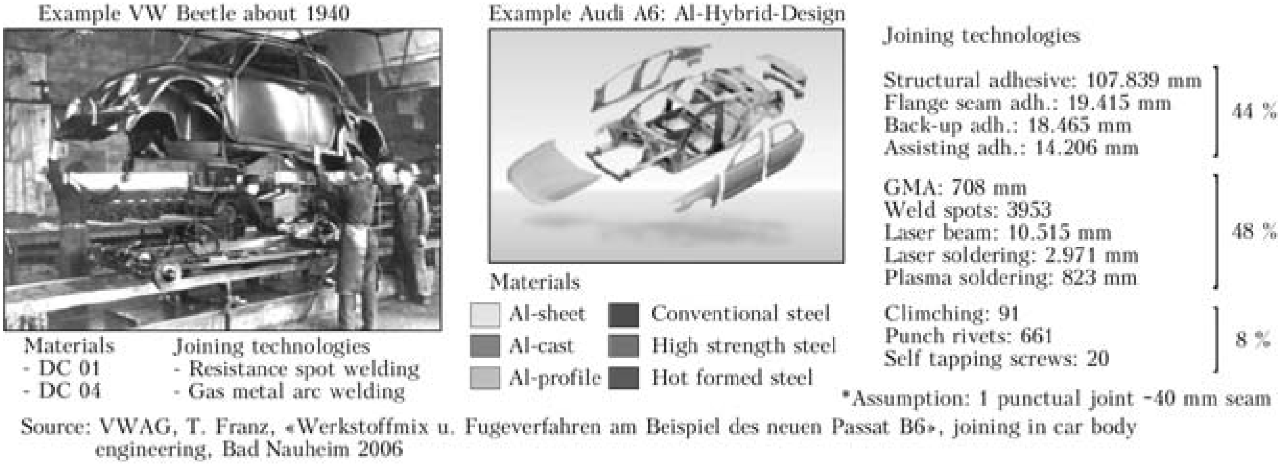

Figure 2. Conventional steel design (*left*) and modern aluminium-steel-hybrid design (*right*)

aluminium or fibre reinforced plastic. This applies in particular to light-weight structures. The production of these applications requires the control over the entire band width of industrially available joining methods in order to identify and qualify the best solution for a specific design under specific production boundary conditions.

The complexity of this task can be clarified by the example of automotive car body design. In the following text this example is used to discuss the question which technology will prevail in the near future: adhesive bonding or welding technology.

Requirements of modern light-weight structures to the joining technique, using the example of the vehicle body construction. In the beginning of the automobile large-scale production, complex structures such as the car body have been joined using a few simple welding methods. Figure 2 (*left*) shows the example of the car body of a VW beetle from the fourties of the last century. The car body has almost exclusively been made using resistance spot welding, supplemented by gas metal arc welding to a small degree. This is, nowadays, unthinkable. Besides increased demands made to corrosion protection, strength and production speed, also the application of most different materials for a car body is, here, particularly responsible.

In the nineties of the last century, aluminium car bodies were to an increasing level introduced to the market and, as a consequence, also aluminium-steel hybrid design structures. Besides this, also pure steel bodies are, nowadays, in principle material mixed constructions. Other than in the car body of the VW beetle where mainly two steel sorts, DC 01 and to a certain degree also DC 04, have been used, modern steel car bodies are made of many different steels, such as deep-drawing steels, high and highest-strength steels and hot-formed steels. Besides this, also fibre-reinforced plastic materials are increasingly gaining in importance in the field of automotive car body construction.

From the perspective of joining, the following important challenges result:

• Joining of materials which are difficult to weld, e.g. highest-strength steels with a defined micro-structur.

• Joining of multi material-mixed compounds, e.g. steel-aluminium, steel-CFK.

• Joining of complex geometries, e.g. combination of plates, profiles, sandwich.

These requirements can no longer be fulfilled with only one joining method. For the production of modern car bodies, therefore numerous joining methods are applied. Besides the established methods resistance spot welding and arc welding, also «younger» welding methods such as laser beam welding, mechanical joining techniques such as clinch riveting and riveting also also adhesive bonding are applied, compare Figure 2 (*right*).

Adhesive bonding vs. welding. Propelled by the request to apply also materials which are difficult to weld or even multi material compounds, research about alternative joining techniques has been promoted. The focus is, on the one hand, on the mechanical joining techniques and, on the other hand, on adhesive bonding. Both technologies are capable of low-heat joining of most different materials with one another.

Compared to the mechanical joining methods, adhesive bonding has several process-related advantages. Adhesive bonding allows the production of optically excellent, leakproof joints with a good corrosion protection and a favourable load transmission using a big joining area. In order to use the advantages also under the high requirements of automotive serial production, several generations of adhesive developments had been required. The most important developments comprise:

- The washout resistance - modern car body adhesives are, also in the non-cured state, not washed out in the paint bath of the cataphoretic immersion priming.
- The oil tolerance - modern car body adhesives are capable to develop good adhesion also on oiled sheets. The expenditure for surface preparation is thus drastically reduced.
- The crash resistance - modern car body adhesives do not suffer brittle failure despite high stiffness and strength. Through the embedding of elastic domains into the stiff matrix, the stress-strain diagram of the adhesives has, in the beginning, a high elastic modulus and transforms in the crash case on a high load level into a deformation plateau.

Due to these developments, the application of adhesive bonding technology in vehicle car body production has, meanwhile, become a standard. The adhesive bonding technology is, thus, directly competing with the welding technology. When working with materials or material mixed compounds which are difficult to weld, the advantages of adhesive bonding will become obvious, also for laypersons. But also pure metal joints are, to an increasing degree, adhesively bonded.

As far as structural tasks are concerned, adhesive bonding is preferentially applied together with spot welding. Attention must be paid to the fact that the main loads are transmitted from the adhesive layer. From the point of mechanics, the weld spots are, above all, minimising the peel load which is unfavourable for adhesively bonded joints. The main reason for the application of spot welding is to guarantee a sufficient handling strength and stiffness of the car body during the production process for the period between adhesive application and adhesive curing.

Having the many advantages of adhesive bonding in mind, the question arises where the welding technology is superior to adhesive bonding. It applies to the joining of metal materials: Adhesive bonding requires a certain expanse in order to transmit the necessary forces. The strength of polymer adhesives is by at least one order of magnitude lower than the strength of metal materials. Especially in the case of only small flange widths or if plate geometries are not to be joined overlapping but on butt joint, the application of welding technology is recommendable. Welding allows, moreover, joining under high thermal load, a robust manufacturing process under rough conditions and the application of established repair concepts.

Furthermore recent developments in the field of welding meet the demands for low expenditure for devices, high productivity and lowest-possible influencing of the base material by a defined heat input. The latter is explained especially from the request to weld also light-weight materials, such as high-strength steels, aluminium or even mixed compounds with good joining properties.

In the field of arc welding, increasingly controlled short-arc processes are applied. Those processes are capable of a defined heat input and allow thus even the joining of aluminium and steel. In the field of laser technology, solid-state lasers which allow high production speed with, at the same time, excellent beam qualities, are applied to an increasing degree. Remote welding processes where the laser beam is deflected via a scanner system with extreme speed, allow meanwhile to achieve welding speeds of up to 20 m/min almost without downtime. For the joining of heat-susceptible materials which lose their good properties permanently through fusion welding, meanwhile joining technologies are used which are capable of working below the fusion temperature, for example ultra-sonic welding or friction stir welding.

Figure 2 makes clear that welding technologies, to a certain degree also mechanical joining methods and also the adhesive bonding technology all have their place with good cause. If sufficient flange areas are provided and especially if materials which are difficult to weld and material compounds are to be joined, the increasing degree of application of adhesive bonding is anticipated.

Since the advantages of both methods are well complementing one another, it is an interesting question whether, in future, better combination possibilities may be found for both technologies. A good example for a successful implementation of this idea is the above-mentioned resistance spot welding adhesive bonding.

Adhesive bonding + welding. In resistance spot weld adhesive bonding, welding and adhesive bonding are combined within one joining zone. While the adhesive bonding guarantees high strength values, stiffness and a good corrosion protection, the resistance spot welding provides above all for the minimising of the peel load and for a high initial strength immediately after the joining process.

The ISF Welding and Joining Institute at RWTH Aachen University (ISF) is working intensely on the development of further possibili-

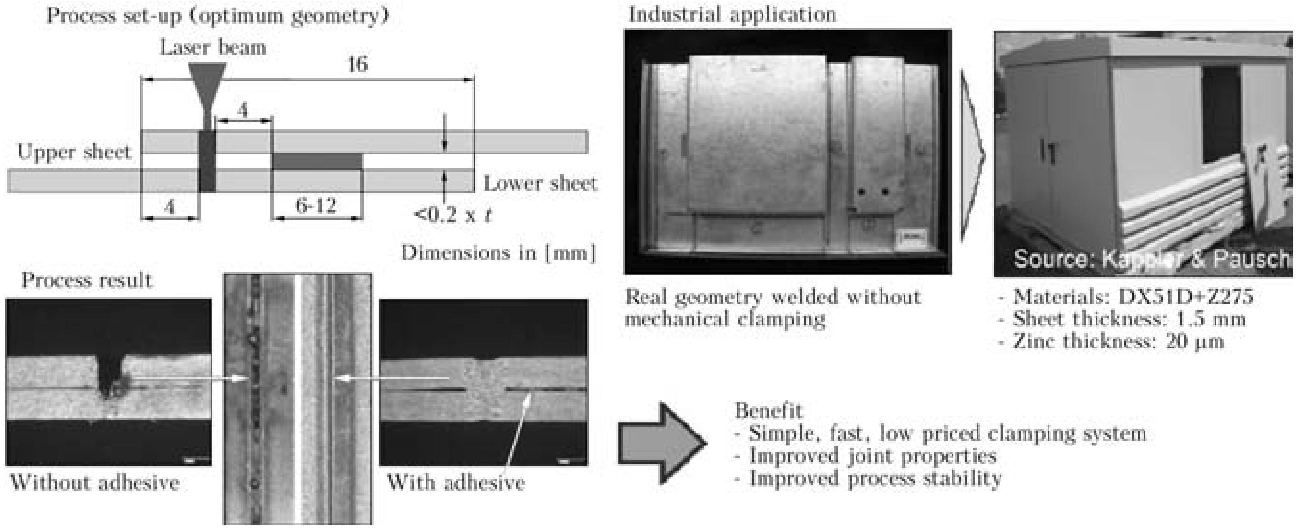

Figure 3. Laser beam welding combined with adhesive bonding

ties for combining welding and adhesive bonding. Thus, among others, the combination of laser beam welding and adhesive bonding and also the combination of friction stir welding and adhesive bonding have been developed and investigated. Both methods will be presented in the following.

Laser beam welding + adhesive bonding. Laser beam welding allows the production of high-quality welded seams with a small heat affected zone at high production speeds. Besides the high investment costs for an industry-standard laser including safety devices, the required clamping devices for a specific joining task represent a substantial cost factor.

In cooperation with the TU Braunschweig together with partners from industry, the ISF has combined the processes laser beam welding with adhesive bonding. While in spot weld adhesive bonding, the bonded seam carries the main load and the weld spots serve mainly for the fixation, it is, here, the opposite. The used adhesives are pressure-sensitive adhesives. These allow the immediate fixation without requiring additional mechanical devices. Since it is not possible to weld straight through the adhesive layer, the advantage of easy and inexpensive clamping comes with larger flange widths, because a certain minimum distance between adhesion and welding must be maintained, compare Figure 3.

Besides the fixation, there are also technical advantages as far as the welding process itself is concerned. During the welding of galvanised sheets with overlap joint, the degassing zinc layer often results in pores in the weld if the sheets are pressed firmly together. To avoid this problem a gap has to be provided between the plates which is so small that the reliable running of the welding process is ensured and which is, on the other hand, so large that the zinc layer is still capable to degas reliably. Gap measures of 0.2 × plate thickness have proven to be recommendable. The clamping of plates with a defined gap measure is extremely complex and requires expensive preparation in terms of clamping devices. Here, the combined process offers the ideal preconditions since, via the adhesive layer thickness, it is be possible to comfortably set the degassing gap without any additional expenditure. Accordingly, very good weld qualities are achieved. The advantages of the degassing gap and of the reduced expenditure for clamping are, especially in the joining of galvanised sheets for small-scale production, outweighing the disadvantages of the larger flange widths and the expenditure for the additional application of the adhesive bonding technology. It has, thus been possible to industrially implement this technology already during the first research project which has been dealing with this subject.

Friction stir welding + adhesive bonding. Based on the successful implementation, the idea has been transferred to friction stir welding. In friction stir welding, tools with a pin and a tool shoulder are used. These tools are set into rotation, subsequently the pin is dipping into the workpiece until the tool shoulder is reaming over the workpiece surface. Via the mechanical rotation and the developing frictional heat, the material is stirred with one another below melting temperature and firmly bonded. Process-related, very high forces are developing which, normally, require clamping devices close to the joining point with high forces. Otherwise, there is the risk of plate warping, Figure 4 (*right*).

The application of the combined process allows to weld almost completely without mechanical clamping technology. It is from a technical point of view, moreover, possible to join thinner

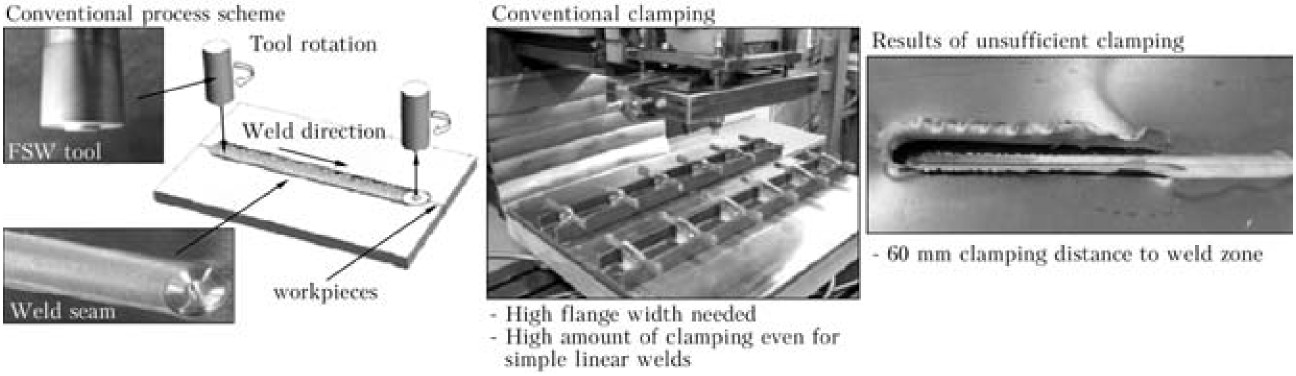

Figure 4. Conventional friction stir welding

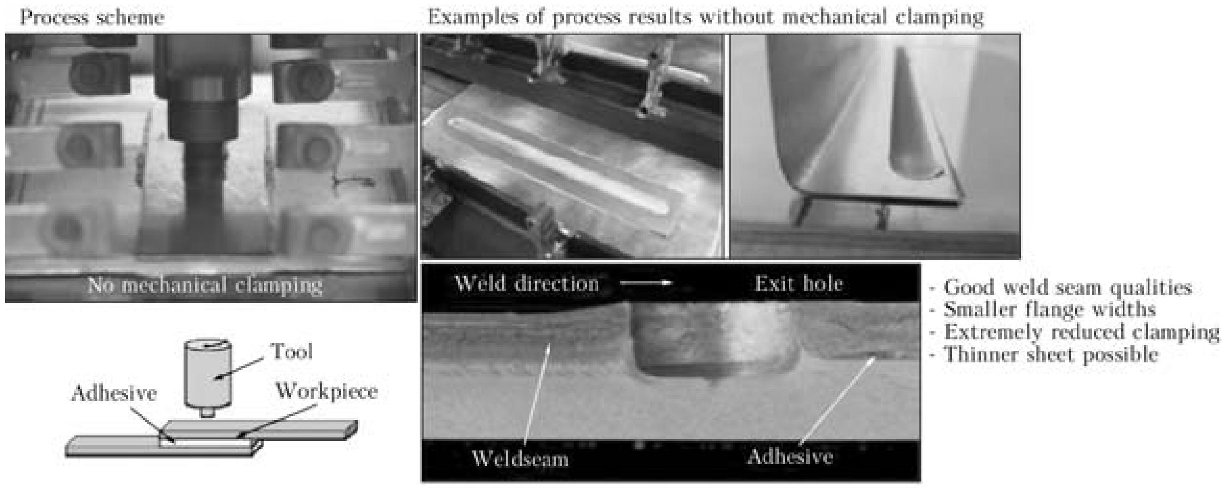

Figure 5. Friction stir welding combined with adhesive bonding

plates due to the lateral load transmission. It is even possible to weld directly through the adhesive layer. The applied pressure-sensitive adhesives are, at that, pushed out and high-quality welded seams are developing, Figure 5. The strength values of the base material are almost achieved. Further advantages, such as reduced cranny corrosion are to be expected and are subject to current research work.

Conclusion

Using the example of automotive car body manufacturing, the application fields of the technologies of adhesive bonding and of welding have been discussed. The application of the welding technology is preferentially used for metal joints, particularly if only small flange widths are available, plates are to be butt-jointed, high application temperatures are prevailing or if immediate strength under demanding production conditions is required. If sufficient adhesive surface is available, the adhesive bonding technology, on the other hand, allows the low-heat joining of most different materials with excellent mechanical properties. It is thus possible to join steels, aluminium alloys and fibre-reinforced plastic materials with most different properties without loss of strength in the base material. The application of the adhesive bonding technology is due to the increasing application of multi material mixed compounds currently also strongly on the rise.

Hybrid technologies which combine the advantages of both methods in one joining zone are particularly advantageous. Besides the already established resistant spot weld adhesive bonding, the ISF Welding and Joining Institute at the RWTH Aachen University has been developing also other process combinations. The combination of adhesive bonding with laser beam welding as well as with friction stir welding was presented. Both of them offer, besides technical advantages, a considerable economical potential through the minimisation of the required clamping technique.

It can already be stated today, that the combined approach between adhesive bonding and welding holds great potentials for future developments.

Received 06.05.2013

RECENT ADVANCES IN THE QUANTITATIVE UNDERSTANDING OF FRICTION STIR WELDING

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Friction stir welding (FSW) is a relatively new welding process and its comprehensive understanding is still developing. While the process is commercially used for aluminum and other soft alloys, its commercial application for the welding of hard alloys will require development of cost-effective and durable tools. Here we review the recent progress made in numerical modeling heat transfer and material flow with particular emphasis on optimizing tool dimensions and selection of welding conditions for maximizing tool durability. 22 Ref., 2 Tables, 6 Figures.

Keywords: *friction stir welding, numerical modeling, heat transfer, material flow, welding conditions, tool durability*

In the last two decades, the applications of friction stir welding (FSW) in aerospace, shipbuilding, transportation and other industries have grown significantly, particularly for the welding of aluminum and other soft alloys [1–3]. General reviews of the FSW process are available in the literature [1–3]. Because melting of the parts is avoided, the process offers several important benefits compared to the conventional fusion welding processes. As a result, there is considerable commercial interest in the friction stir welding of steels and other hard alloys [4–6]. The FSW process involves several simultaneous physical phenomena that affect the durability of the tool and the structure and properties of the welded material. Heat is generated due to both the interfacial friction between the tool and the work piece and the plastic deformation of work piece material. The work piece material is softened close to the tool and the plasticized material flows due to rotation and the linear movement of the tool.

FSW is a relatively new process, and because of the complexity of the process a comprehensive understanding of the process is still evolving [7–13]. Therefore, it is useful to undertake a review of the current status of quantitative understanding of the process. Here we review our recent research on numerical modeling of heat transfer and material flow in FSW and how it can be used for the solution of two important contemporary problems. First, the application of the heat transfer and material flow model to estimate the optimum tool dimensions is discussed. Second, we show that the model can be used to enhance longevity of the FSW tools, particularly for the welding of hard alloys.

Optimum shoulder diameter. The diameter of the tool shoulder is important because the shoulder generates most of the heat, and its grip on the plasticized material largely establishes the material flow field [14–15]. Both the heat generation rate and the material flow are important for the FSW process. With the increase in the shoulder diameter, the temperature increases and the work piece material is softened. For a good FSW practice, the material should be adequately softened for flow, the tool should have adequate grip on the plasticized material, and the total torque and power should not be excessive [15]. Experimental investigations have shown that only a tool with an optimal shoulder diameter results in the highest strength of the AA6061 FSW joints [16]. Although the need to determine an optimum shoulder diameter has been recognized in the literature, the search for an appropriate principle for the determination of an optimum shoulder diameter is just beginning [14–15].

We recently proposed [14, 15] a method to determine the optimal shoulder diameter for the FSW of aluminum alloys by considering the sticking (M_T) and sliding (M_L) components of torque. The main engine for the calculations is a steady three dimensional heat transfer and material flow model which was validated for friction stir welding of aluminum alloys, steels and a titanium alloy [7, 8, 10]. The torques were calculated based on the tool geometry, flow stresses in work piece, and the axial pressure (PN) as [14, 15]

$$M_T = \oint_A r_A (1 - \delta) \tau dA, \quad (1)$$

$$M_L = \oint_A r_A \delta \mu_f P_N dA, \quad (2)$$

where r_A is the distance of any infinitesimal area element, dA, in work piece material from the tool axis; d and m_f are spatially variable fractional slip and coefficient of friction between the tool and the work piece, respectively, and t is the shear stress at yielding. The tool rotation speed and the radial distance from tool axis affect the local values of d and m_f [14, 15]. The total torque, M is the sum of sticking and sliding torques. The required spindle power (P) can be calculated from the total torque as [14]

$$P = \oint_A r_A\{(1 - \delta)\tau + \delta\mu_f P_N\}\omega r_A dA, \qquad (3)$$

where ω refers to the angular speed in rad/s.

Figure 1 shows that for the FSW of AA6061, the sliding torque continuously increases with shoulder diameter because of the larger tool-work piece interfacial area. However, the sticking torque increases, reaches a maximum and then decreases. This behavior can be understood from equation (1) that includes the two important factors that affect the sticking torque. First, with the increase in shoulder diameterthe area, A, increases, the temperature rises and the shear stress at yielding, t, decreases. The product of these two opposing factors lead to a maximum value of sticking torque in the plot of sticking torque versus shoulder diameter. This value of sticking torque indicates the maximum grip of the shoulder on the plasticized material [14, 15]. The calculated results show that any further increase in the shoulder diameter will result in decreased grip of the tool on the plasticized material, higher total torque and higher spindle power requirement. For these reasons, the optimum shoulder diameter should correspond to the maximum sticking torque for a given set of welding parameters and work piece material [14, 15].

Figure 2 shows the variation of sticking torque with shoulder diameter for various tool rotational speeds for the FSW of 7075 aluminum alloy. The shoulder diameter at which the maximum sticking torque is attained depends on tool rotational speedwhenall other welding variables aremaintained constant. For the rotational speeds indicated in the figure, the optimum values of the shoulder diameter are in the 20 to 30 mm range for the various parameters used in the experiments. Since the 7075 alloy is harder than the 6061 aluminum alloy, the computed larger optimum shoulder diameters compared with those estimated for the FSW of 6061 is consistent with the larger heat demand for the FSW of 7075 alloy. The results show that the principle of optimizing shoulder diameter by maximizing tool's grip on the plasticized material can be applied to different alloys. Since tool durability and cost-effectiveness are crucial issues for successful commercial application of FSW to steels and other hard alloys, a general principle for the optimum design of shoulder diameter based on scientific principle such as the one discussed here is important.

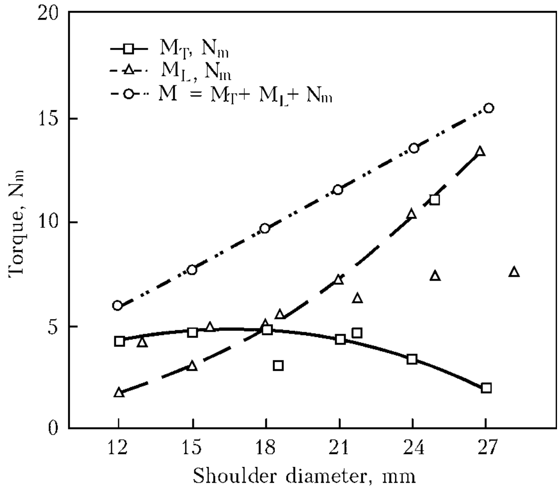

Figure 1. Variation in sliding (M_L), sticking (M_T) and total torques with shoulder diameter for FSW of 6 mm thick AA6061 at a tool rotational speed of 1200 rpm and welding speed of 1.25 mm/s^{-1} [15]

Pin geometry. Since tool pins often fail during welding of hard alloys, a systematic investigation of the various tool materials and their load-bearing abilities are important [17]. In particular, the pin being the structurally weakest section of the FSW tool, an estimation of the load bearing ability of the tool pin is required for efficient functioning of the FSW process. Although some measurements and calculations of the forces on the tool have been reported in the literature, a procedure to calculate the load bearing ability of the tool pins of different shapes is of interest [18, 19]. Such a methodology has beendiscussedrecently based on the calculation of maximum stresses experienced by the tool pin resulting from a combi-

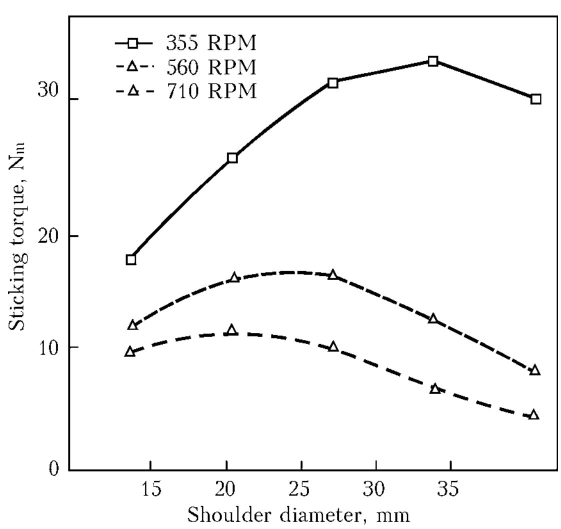

Figure 2. Variation of sticking (M_T) torque with shoulder diameter for FSW of 3.5 mm thick AA7075 at a welding speed of 0.67 mm/s [14]

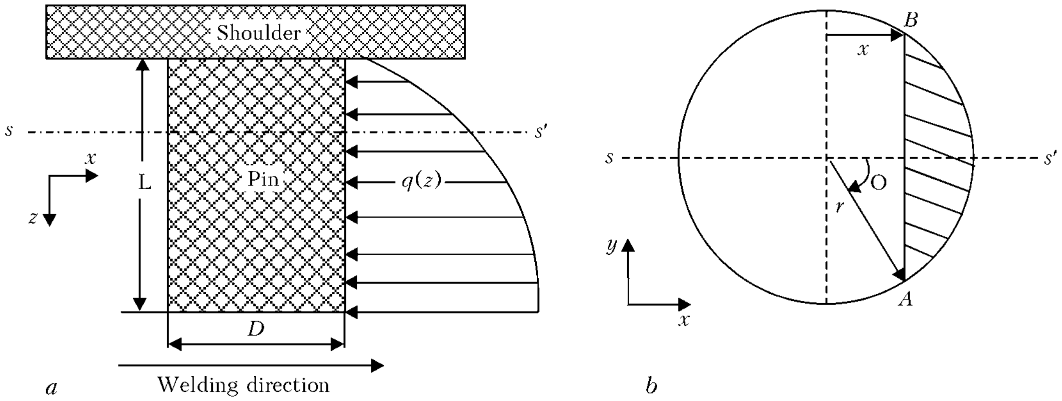

Figure 3. Schematic distribution of force on a typical straight cylindrical tool pin (*a*) and cross-section of pin profile along section S-S.18 (*b*)

nation of torsion due to torque and bending due to traverse force [18, 19].

Figure 3, *a* shows a schematic force distribution, $q(z)$, on a straight cylindrical tool pin in FSW. It can be noted that the force distribution, $q(z)$ would be in adirection opposite to the welding direction. Figure 3, *b* depicts a transverse cross-section of the tool pin along S-S in Figure 3, *a*. The bending moment (M_y) experienced at any point A on the tool pin profile can be estimated as [18]:

$$M_y = \int_{z_1}^{L} zq(z)dz, \tag{4}$$

where L is the length of pin; z_1 is the distance of the point A from the root of the pin; $q(z)$ is the force on an infinitesimal part, dz, of the pin at a distance $(z + z_1)$ from the root of the pin. The normal stress due to bending, σ_B, and the shear stress due to torsion, τ_T, and also due to bending, τ_B, on any point A on the pin profile can be estimated further as [18]

$$\sigma_B = \frac{M_y x}{I_{yy}}, \tag{5}$$

$$\tau_T = \frac{M_T r}{J_z}, \tag{6}$$

and

$$\tau_{TB} = \frac{VQ}{I_{yy} g}, \tag{7}$$

where I_{yy} and J_z are the second moment and polar moment of inertia for the pin structure, respectively; M_y and M_T are the bending moment and sticking torque, respectively; V is the shear force and Q is the first moment of inertia of the section beyond chord AB (in Figure 3, *b*) about the neutral axis; x is the normal distance between the neutral axis and the chord AB; r is the pin radius and g is the length of the chord AB. These components of stresses can be used to compute the resultant maximum shear stress, τ_{max}, experienced by the tool pin as [18]

$$\tau_{max} = \sqrt{\left(\frac{\sigma_B}{2}\right)^2 + (\tau_B + \tau_T \sin\theta)^2 + (\tau_T \cos\theta)^2}. \tag{8}$$

It follows that t_{max} times a safety factor, f, should be lower than the shear strength of the tool material at the prevailing working temperature to avoid premature shear failure of the tool pin in the operating range of process parameters.The pin length depends on the thickness of the work piece. The geometry of the pin must be determined based on its load bearing ability, i.e., the ability to withstand the maximum shear stress.

The traverse force on the pin increases with increase in the pin length as shown in Figure 4. As the plate thickness increases, pins of longer lengths are required. A longer pin experiences higher resultant maximum shear stress and a larger cross-sectional area of the pin becomes necessary to avoid pin failure. However,as the pins of large diameters move forward, plasticized alloys must fill up the void space left behind by large pins. Any disruption of the flow of plasticized material or a small reduction in temperature will enhance the occurrence of defects such as worm-holes.The traverse force on the tool can be measured using a dynamometer, and the values can be used to monitor defect formation during FSW because the large forces indicate sluggish material flow. Thus, the lower limit for the tool pin diameter can be prescribed from the calculation of the maximum shear stress on the tool pin and the upper limit for the pin diameter can be estimated considering the weld quality.

The load bearing abilities of pins with circular, square and triangular cross-sections have been compared [19] under similar welding conditions. For comparison of the three cross-sections, the triangular cross section is considered to be of equilateral shape and thetriangular and the square cross-sections are considered to have dimensions that fit within the circular pin profile. It is found that the lowest and the highest values of the maximum shear stress are experienced by the circular and the triangular pin cross-sections,

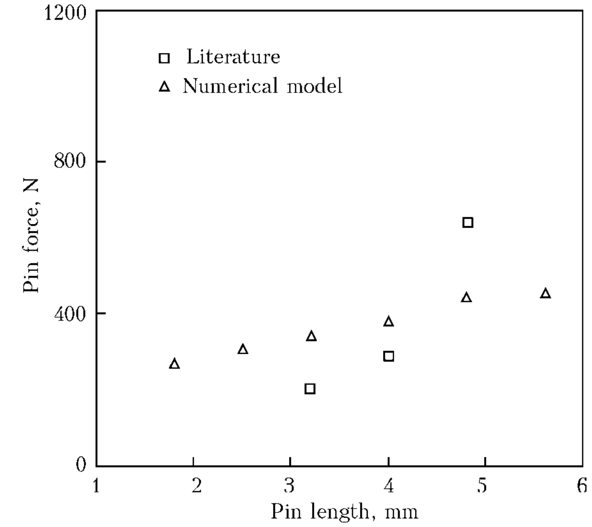

Figure 4. A comparison of computed and corresponding estimated values of traverse force on tool pin in FSW of AA6061 at tool rotational speed of 650 RPM, welding velocity of 3.33 mm/s and pin diameter of 7.6 mm [18, 20]

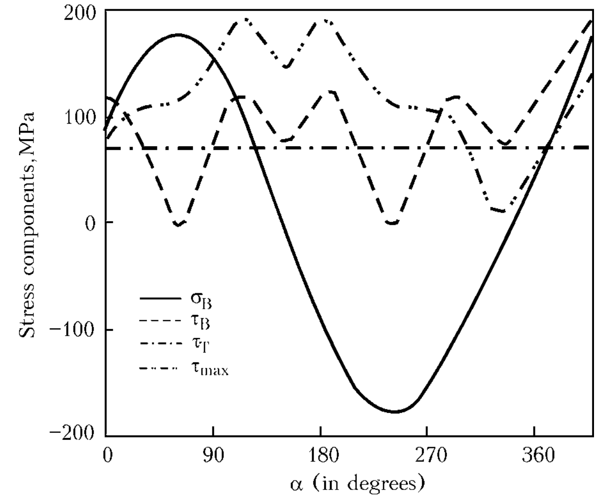

Figure 5. Variation of fluctuating stress components — normal stress for bending, σ_B, shear stress due to bending, τ_B, shear stress due to torsion, τ_T, and the maximum shear stress, τ_{max} for one completerotation of the tool during FSW of AA7075-T6 usingtriangular pin profile [19]

respectively. During one complete rotation, the triangular pin cross-section experiences the largest fluctuation of the maximum shear stressfollowed by the square and the circular pin profiles. Figure 5 shows the typical fluctuation of various stresses during rotation expressed as a function of angle with the welding direction. The large fluctuation of maximum shear stress during rotation makes the triangular cross section susceptible to fatigue failure.

Durabilityof FSW tool. Since the tool pin is structurally the weakest section of FSW tool, itsdegradation due to plastic deformation or wear as well as its ability to withstand the torsion and bending stresses are of significant concern. A review of the currently used and potential tool materials is available in the literature [17]. The material to be used for FSW tool should be cost effective and have high strength, hardness and good toughness, and high melting and softening temperatures [17]. Furthermore, the geometry of the tool pin for a given material should also be assessed for its low susceptibility to premature failure for various values of FSW variables. Recently, a tool durability factor has been proposed that can indicate whether the thermo-mechanical environment experienced by a tool pin for a given FSW condition is safe enough to avoid a premature shear fracture [21, 22]. The tool durability factor does not consider vibration and other

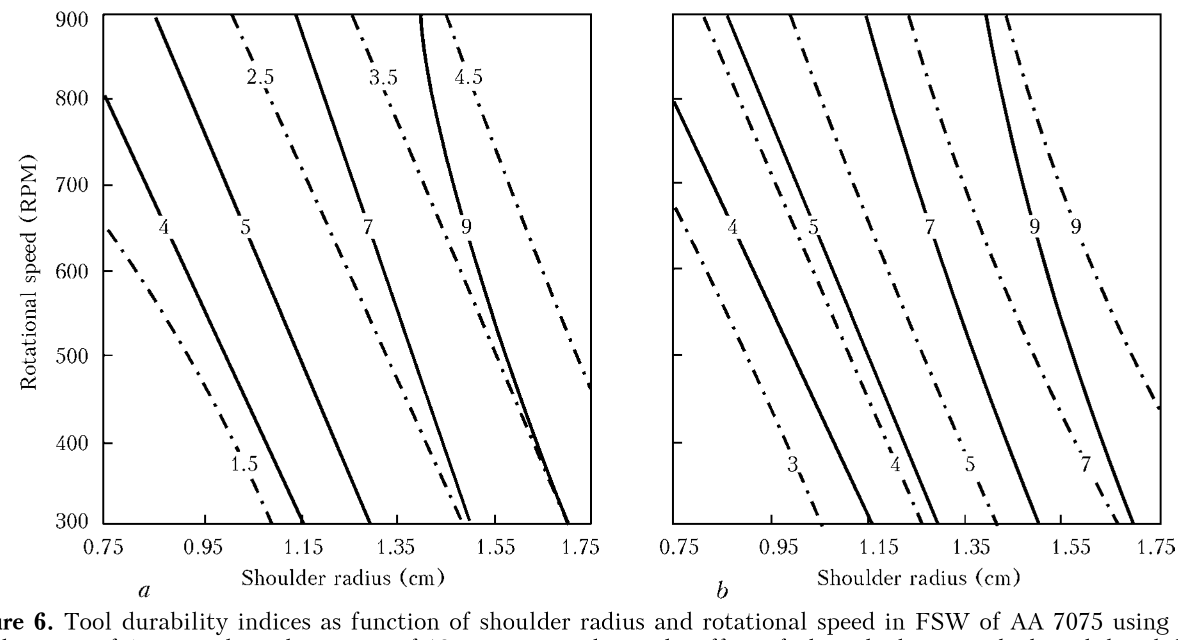

Figure 6. Tool durability indices as function of shoulder radius and rotational speed in FSW of AA 7075 using a tool pin diameter of 4 mm and axial pressure of 18 MPa: *a* — shows the effect of plate thickness with the solid and dashed lines referring to thinner (2.9 mm) and thicker (5.7 mm) plates, respectively, at a welding speed of 1.0 mm/s; *b* — shows the effect of welding speed with the solid and dashed lines depicting the lower (1.0 mm/s) and higher (4.5 mm/s) speeds, respectively for a plate thickness of 2.9 mm [22]

abrupt causes of tool degradation. However, the progressive degradation of the tool pin may be minimized by focusing on the relative severity of maximum shear stress it experiences for various welding conditions. The tool durability factor is defined as the ratio of the shear strength of the tool material at the peak temperature and the resultant maximum shear stress experienced by the tool pin due to bending and torsion.

Figure 6 shows a typical tool durability mapfor various tool shoulder radius and rotational speed for the FSW AA7075 alloy. A comparison of the solid and dashed lines in Figure 6, *a* shows how the tool durability index or the factor of safety for the tool pin changes with the change in plate thickness. During FSW of thick plates, there is considerable decrease intemperature away from the tool shoulder and the pin encounterscooler and stronger workpiece material near the lower part of the pin. As a result, tools encounter large stresses during welding of thick plates and the tool durability decreases with increase in plate thickness. Similarly, a comparison of the solid and the dashed lines in Figure 6, *b* shows that an increase in welding speed reduces the value of tool durability index. Similarly an increase in the welding speed reduces the rate of heat generation per unit length of weld resulting in relatively colder material around the tool pin. As a result, the tool durability index decreases with increase in welding speed.

Conclusions

Because FSW is a new and complex process, its comprehensive understanding is still developing. Unlike other welding processes, its existing knowledge base cannot be relied upon for solving important contemporary problems such as extending its reach to harder materials such as steels and titanium alloys. Well tested heat transfer and material flow models provide a recourse to address the important issues based on solid scientific principles. The examples reviewed here show how the quantitative understanding of heat transfer and material flow offer new insights about optimizing tool design. Both the optimization of shoulder diameter and the consequences of alternative tool pin shapes can be examined based on well tested numerical models. In the past, the sophisticated numerical models of heat transfer and materials flow in welding have not been widely used in industry.In recent years, the modeling results for FSW have been presented as easy to use process maps,enabling practicing engineers to select welding conditions based on scientific principles to extend tool life. Apart from revelingsignificant insight about the FSW process, the numerical models of heat transfer and materials flow can also providesignificant competitive technological advantage.

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Received 21.06.2013

INNOVATIVE TECHNOLOGIES IN THE FIELD OF STRUCTURAL STEELS AND THEIR WELDING

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The retrospective review of cooperation between the Central Research Institute of Structural Materials «Prometey» and the E.O. Paton Electric Welding Institute in the field of development of super reliable metallic materials and industrial technologies for special engineering, development of covered electrodes, agglomerated fluxes, flux-cored wires, welding technologies and equipment was studied. The common approach was used to the developments of technology of metallurgy and welding with the final aim to provide the high service reliability of modern structures manufactured on the basis of new materials. The joint works on evaluation of resistance of materials to brittle fractures, development of methods for evaluation of cyclic life of welded structures, improvement of methods for certification tests of metal were outlined. 2 Tables, 4 Figures.

Keywords: *innovative technologies, structural steels, welding consumables, service reliability, nanotechnologies and nanomaterials, cooperation*

The joint works with the E.O. Paton Electric Welding Institute in the Soviet years and in the post-Soviet period laid grounds to research directions of works which found their further progress at the Central Research Institute of Structural Materials «Prometey» in the development of super reliable materials and industrial technologies for special engineering, applied under the extreme conditions. The most significant of them are devoted to the developments of electroslag remelting (ESR) technologies of high-strength weldable steels, development of high-quality welding consumables and also providing operation reliability of large-size welded structures.

The ESR method was developed at the beginning of the 1970s of the past century in collaboration between the scientists of the E.O. Paton Electric Welding Institute, the Central Research Institute of Structural Materials «Prometey», the I.P. Bardin Central Research Institute of Ferrous Metallurgy and specialists of metallurgical plants of Ukraine. The main task, requiring solution, was to increase the metallurgical quality and eliminate the anisotropy of properties of thick-plate rolled metal of high-strength steels for prevention of brittle fractures. The new technology allowed considerable reduction in the content of sulfur, oxygen, non-metallic inclusions (Figure 1), providing 2–3 times increase in ductility and impact toughness values (Table 1); decrease of critical temperatures of brittleness, increase of resistance to crack propagation; maximum restriction of carbon content, regulating the content of alloying elements within the narrow limits.

This allowed widening the assortment and providing production of large-size sheet rolled metal, high uniformity of structure and mechanical properties along the area of a large-size sheet and in the direction of its thickness, improving weldability and increasing stability of mechanical properties in the heat-affected zone of welded joints. The steel turned in principle into the isotropic material.

The transition of Russian enterprises to the market relations required the new methods of melting, i.e. those applying the complex of ladle treatment (ladle refining and degassing). The

Table 1. Mechanical properties of high-strength steels

Method of melting	δ_5, %	ψ, %	KCV, J/cm^2	ψ_z, %
ESR	17.0–21.5	64–70	128–300	50–55
Ladle refining	17.0–20.5	64–68	124–235	40–55

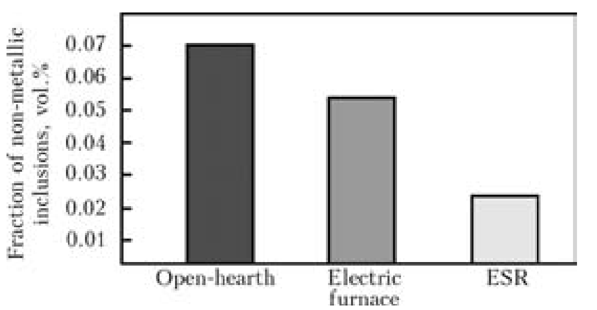

Figure 1. Content of non-metallic inclusions in high-strength steel of different melting

Table 2. Service characteristics of weld metal in flux-cored wire welding

Grade of flux-cored wire	R_m, MPa	R_e, MPa	A_5, %	KV, J
48PP-8N	510–650	440–480	22–28	75–90 (–20 °C)
48PP-11N	610–770	500–530	20–24	60–80 (–40 °C)
PP-SVP1	650–710	500–550	23–27	75–90 (–40 °C)
48PP-10T	545–560	460–480	22–25	60–80 (–60 °C)

experience of application of ESR technology allowed transition to radically new scheme of production of metal with the quality not inferior to the metal produced by ESR (Table 1). It should be noted that ESR method allows producing new high-quality products (for example, during production of nitrogen steels) developed in the Central Research Institute of Structural Materials «Prometey».

The Central Research Institute of Structural Materials «Prometey» together with the E.O. Paton Electric Welding Institute carried out the joint works on the development of covered electrodes, agglomerated fluxes for automatic welding, flux-cored wires of small diameter and also welding technologies and equipment. The new challenging welding consumables are developed on the basis of optimization of systems of alloying, microalloying and modifying of weld metal to provide the required operating efficiency of welded joints (including those at the negative temperatures), high weldability and crack resistance.

The new highly-technological flux-cored wires of small diameters for welding of steels with the yield strength from 360 to 550 MPa with the level of operation characteristics not inferior to the best foreign analogues were created and the industrial technology of their manufacture was developed (Table 2).

The series of developed covered electrodes of fluorite-calcium type allows providing a low content of diffusion hydrogen in the deposited metal, stable high service characteristics, preset level of strength and ductile properties of weld metal in welding of cold-resistant steels.

For automatic submerged arc welding the agglomerated fluxes in combination with different wires were developed providing complex of necessary service characteristics. The industrial production of fluxes was mastered on the production facility of the Central Research Institute of Structural Materials «Prometey», Figure 2. The distinctive feature of the developed fluxes is their high competitiveness based on the high technological efficiency of welding process and cost-effectiveness.

The principally new technology of welding flux production using laser granulation was developed to provide the low hygroscopic properties of the flux; possibility of deoxidation, alloying and modifying of weld metal through the flux; low content of diffusion hydrogen in the deposited metal and also relatively high strength of flux granules. The implementation of a new flux in the production allows decreasing the temperature of preliminary and concurrent heating in welding; performing welding of high-strength steels with the yield strength of more than 800 MPa; considerably increasing the service characteristics of welded joints.

The submerged multiarc welding, widely used in the pipe industry, with the developed new welding consumables during its implementation in the ship building allows considerable increasing of labor efficiency and maximum automation of production cycle in plane sections manufacture.

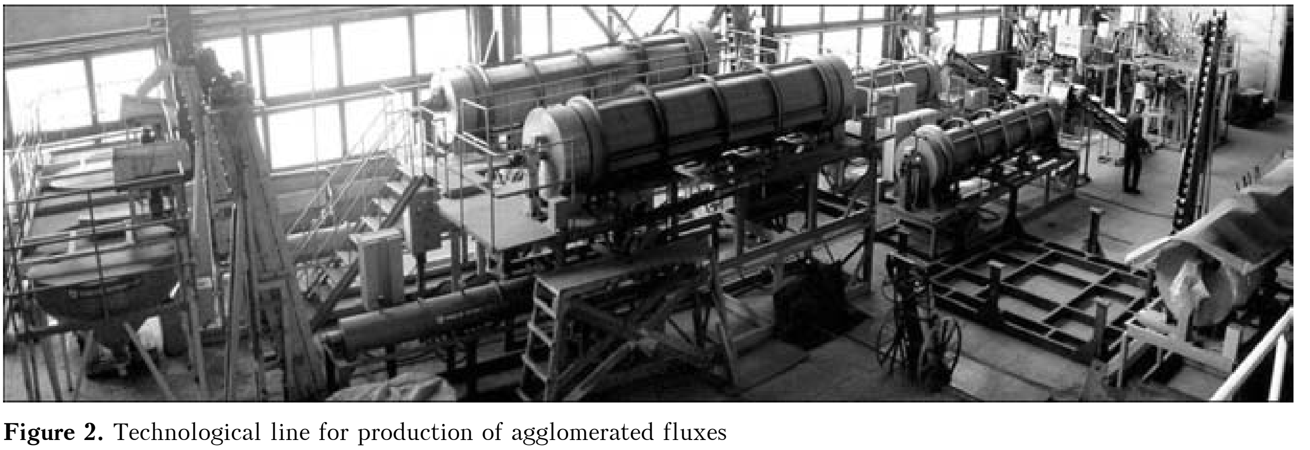

Figure 2. Technological line for production of agglomerated fluxes

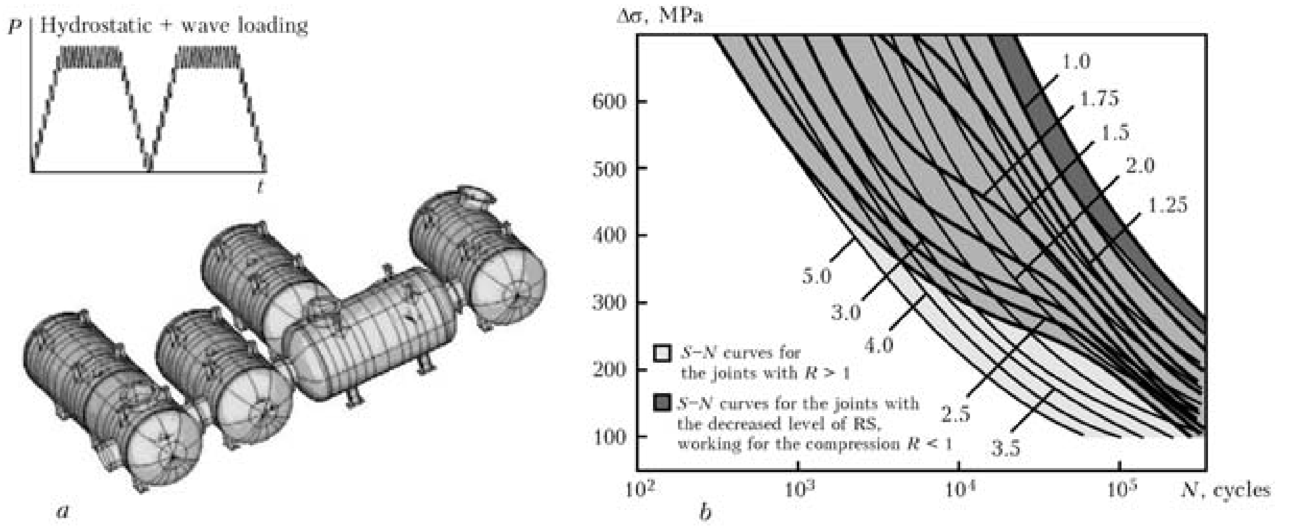

Figure 3. Calculated evaluations for selection of design of a barocomplex units: *a* — system of barochambers; *b* — calculation curves of admissible fatigue damages

The high-efficient electrogas welding along the slot groove till now remains unsurpassed in producing slot welds of structures of high-strength steels. The mentioned technology provides possibility of welding the high-strength steels without preheating using low-alloyed wires, high quality of metal of welded joints and process efficiency.

Over the period of cooperation between the Central Research Institute of Structural Materials «Prometey» and the E.O. Paton Electric Welding Institute the common approach to the developments of metallurgy and welding technologies was applied. The aim of the developments was not only the creation of new materials, but also providing a high operation reliability of structures made of these materials. The set aim requires the solution of three problems: development of scientifically-grounded requirements to the materials, their comprehensive certification, and also works directed on «fitting» of structures to the material. To solve the first and the third problems the development of calculation methods for evaluation of strength and life is necessary from which both the grounds of requirements to the material as well as grounds of requirements to the design of welded elements should result.

To provide the reliability of structures operating under the arctic conditions, the development of methods for evaluation of resistance to brittle fracture is challenging. Its task consists not only in determination of requirements to cold resistance of metal of welded joints but also in the efficiency and volumes of non-destructive testing methods. Namely such an «inverse» problem had to be solved evaluating the possibility of operation of a structure manufactured for the higher calculation temperatures under the arctic conditions.

The development of methods of evaluation of cyclic life of welded structures was also beginning from the joint works with the E.O. Paton Electric Welding Institute: the influence of two-frequency loading on fatigue strength of the structures was investigated. The example of similar task solved at the moment is implied in selection of design of units of a barocomplex, installed on the deck of a ship, using calculated evaluations (Figure 3). Here, the low-cycle loads due to changes of internal pressure in barochambers are added by the second frequency loads connected with the wave loads to the deck.

The new tasks connected with the construction of pipelines of high reliability in the arctic regions require also the updating of methods of certification tests of metal. To control the energy capacity of metal fracture of main pipelines the methods for determination of energy of plastic deformation during crack propagation at dynamic tests on the unique as to its energy capacity vertical impact tester of 60 kJ were mastered, the necessity in conduction of tests on crack resistance of metal of welded joints at different schemes of loads was shown, the methods of control of a new parameter, i.e. critical angle of crack opening (CTOD), was offered.

To investigate the life of new pipe products the stand was created (Figure 4) allowing simulating the real spectrum of loading of pipes, used in gas- and oil pipelines. The results of full-scale tests prove the necessity of their use in the critical structures, i.e. the integral verification of the whole technological line of production allows revealing the «weak spots» which are not detected during tests of standard specimens.

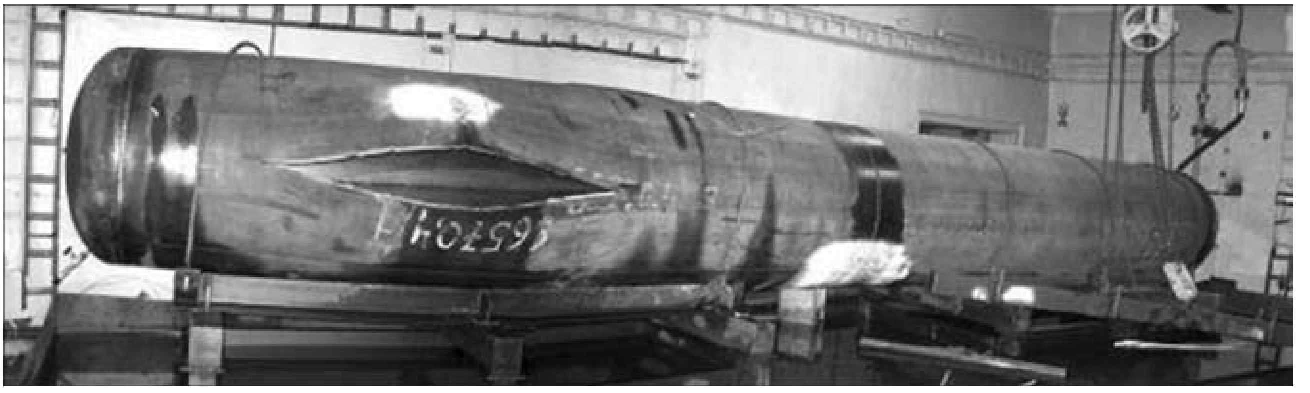

Figure 4. Stand for service life tests of pipe elements of up to 6 m length

The mutually-developed welding consumables, technological processes and methods of strength evaluation allow manufacturing the metal structures with guaranteed high service characteristics (from the regions of the Extreme North to the highly-aggressive conditions of tropical latitudes).

One of the further directions of radical increase of consumer qualities of materials are nanotechnologies and nanomaterials developed at the E.O. Paton Electric Welding Institute and also application of surface engineering. Developed are the technologies of evaporation condensation (magnetron, ion-plasma and atomic-ion spraying) with the controlled plasma flow, supersonic «cold» gas-dynamic and microplasma spraying, electrolytic modifying of nanostructured surface, laser prototyping of nanocomposite powders, controllable crystallization from the amorphous state.

The further development of hull materials will take place due to synergetic effect on the basis of new scientific knowledge in the physics of strength, plasticity, materials science, physical-chemical processes of welding and nanotechnologies. Such is the way of the challenging cooperation.

Received 12.04.2013

TRENDS IN DEVELOPMENTS IN GAS SHIELDED ARC WELDING EQUIPMENT IN JAPAN

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In the welding field in Japan, new technologies and processes have been developed one after another in response to the improvement in materials and the changes in the market needs, which have remarkably been contributing to rationalization and cost reduction in various industries. Taking into account the abovementioned technological trends, this paper provides an overview of the present situation of technological developments in terms of gas shielded arc welding equipment. 16 Ref., 2 Tables, 10 Figures.

Keywords: *trends, technology, welding equipment development, MAG, MIG, TIG welding*

It has passed one century with the arc welding technology since 1904 when Oskar Kjellberg, a shipbuilding engineer in Sweden, developed and practiced the shielded metal arc welding process. The shielded metal arc welding process was introduced in shipyards in Japan about ten years later than that time, and in the 1920s, the first domestic DC arc-welding machine was born. Afterwards, the submerged arc welding process and the gas shielded arc welding processes such as TIG and MIG were developed and practiced one after another in Europe and the United States from the 1930s to 1940s. These welding processes were introduced in Japan, too, nearly ten years later after the employment in the Western countries.

In the early 1950s, the submerged arc welding machine was developed with the domestic technologies. Since then, the performance and quality of the domestic arc-welding equipment have earned a giant leap in tandem with the advancement of the heavy industries such mainly as shipbuilders and bridge fabricators. This became the trigger of shifting the main usage of the Western-made arc welding machines to the Japanese-made ones in fabrication sites. In the 1970s, the traditional major processes of submerged arc welding and shielded metal arc welding were superseded gradually by GMA welding, mainly CO_2 arc welding and MIG welding. This has urged the development of GMA welding equipment. The 1980s was special in that the articulated arc-welding robot became popular and the welding power source of the transistor-inverter controlled type was developed, and thereby the arc welding equipment was improved associated with the advancements in the power electronics; as a result, the technical development for higher efficiency and automatization in welding has been progressed until today.

This paper reports the performances and functions of the welding equipment developed in the last ten years aiming at the achievement of high-quality or high-efficiency in GMA welding.

The history of development of the GMA welding power source in Japan. *The trend and growth of the output control method for the GMA welding power source*. Figure 1 shows a summary of the trend and growth of the output control method for the welding power source for GMA welding in Japan for the last 30 years.

Though the step or slide-transform control type has decreased in the production quantity ratio, it is still used steadily at a ratio of about 5 %, mainly in the sheet-metal welding workshop. The thyristor control type, which was dominant for the output control method till the 1970s, is still used mainly in the fabrication sites for medium/thick plate welding constructions in shipbuilders and building constructors, with a volume ratio of around 20 %. Since the welding power source of the inverter control type with power transistor was developed in the early 1980s, the production volume ratio rapidly expanded by the early 1990s. In the latter half of the 1990s, developed was the digital inverter control type, which features the inverter for controlling the output and the software for controlling the welding current and voltage waveforms to govern the welding performance and function. This control type has earned a rapid growth of use since the 2000s, reaching a quantity ratio of nearly 70 % today.

Trends in the technology development for GMA welding power source. Figure 2 shows a

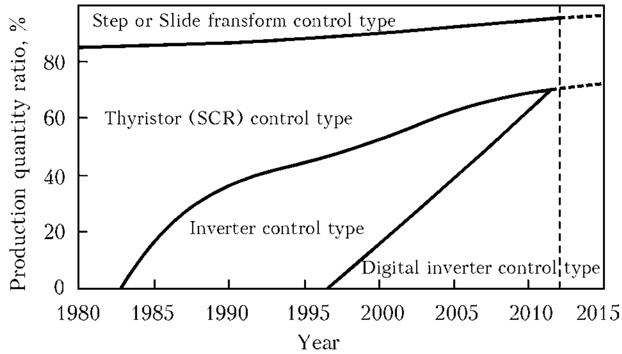


Figure 1. Change in spread of power source control type in Japan

summary of the recent trends in the development of the major control technologies for the arc welding power source [1]. The thyristor-controlled power source was developed in 1969, which led the development of the welding sequential control and the unified control for improved performance. The low-frequency pulse control and the medium-frequency pulse control with a fixed pulse frequency were also practiced.

The pulse power source with the synergic pulse process on board was developed in 1980 and was marketed as the welding power source equipped with the world's first, general-purpose, low-priced transistor for the output control by the transistor chopper. This type of power source became the prototype of the present pulse MAG/MIG welding power source. However, in 1983 after three years, the practice of the inverter-controlled welding power source highly expanded, resulting in the development of the pulse MAG/MIG welding power source of the inverter control type that featured high-speed output control. This development caused the pulse MAG/MIG welding power source of the transistor-chopper control type to become disused shortly.

Afterwards, all the advancements in the welding power source were based on the inverter control type. In 1990, the high-function/performance welding power source that was combined with the microcomputer control was developed [2, 3]. In 1992, the intelligent welding power source with the fuzzy control on board was developed [4, 5].

At the end of the 20th century, it was started to apply highly the digital control to the welding power source, with the background of advancement in the digital control technology; i.e., the majority of the control circuits were engineered to change the analog control to the digital control to improve the reproducibility of welding conditions [6]. Recently, it has actively been promoted to increase the output control speed by using the high-speed control element; as a result, the high-performance welding power source, that can control the welding and arc phenomena in almost the ideal modes, has also been marketed [7].

Table 1 shows a summary of the performances of the microprocessors applied to the welding power sources of the digital inverter-control type. In 1996, the digital control (with software) was employed for all the controls of the welding current and voltage waveforms to regulate the arc welding process [8]. At that time, 16-bit microprocessor was used to enable a single-chip micro-

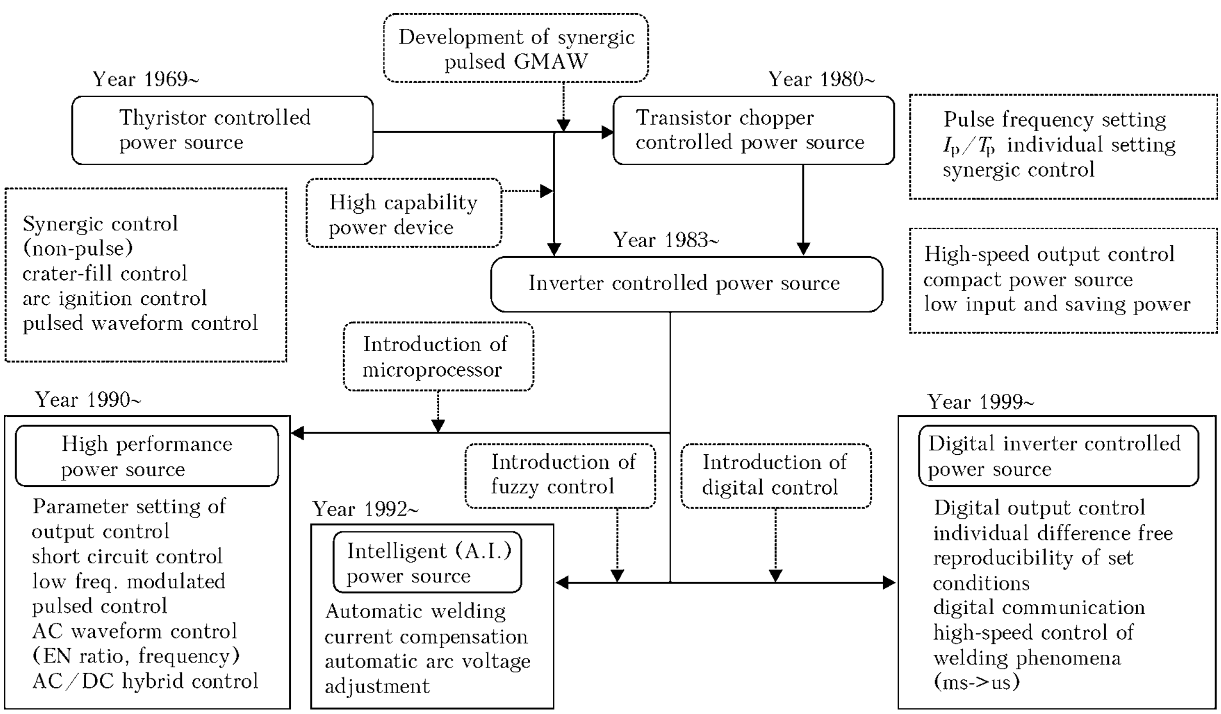
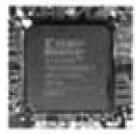


Figure 2. Trends in developments of main control technology for arc welding power source

Table 1. Change in micro processor and welding power source

	The first generation 1996-2000	The second generation 2001-	The third generation 2008-	The fourth generation 2010-
Power source			FPGA   FPGA: all-purpose LSI, in which plural DSP and CPU are assembled in 1 chip.	ASIC   ASIC: LSI optimum for welding control, in which plural DSP, CPU and analog circuit are assembled in 1 chip.
Micro processor	16 bit	32 bit/DSP	FPGA	ASIC
Processing cycle	100 ms	25 ms	1ms	20 ns
Processing capability	1	4	16	64

DSP: Digital signal processor
FPGA: Field progrfmmable gate array
ASIC: Application specific integrated circuit

computer to execute multiple controls, including the optimizing control of pulse parameters and the fuzzy control for automatic adjustment of welding current and voltage, thereby eliminating the need of individual logic circuits. In 2000, 32-bit microprocessor, which features the two times or higher control frequency and 4–8 times capacity as compared to the conventional type, began to be applied. With respect to the control speed, the digital signal processor (DSP) that enables the direct control with software has provided the fast-acting output control by inverter [9]. Lately, the field programmable gate array (FPGA) with a highly-integrated circuit that unifies 32-bit microcomputer and DSP has been employed in the welding power source, and thereby the control speed and program capacity have been improved by 1- or 2-digit magnitude as compared to those used in ten years ago. These microprocessors used in the welding power source are commercial ones. In order to realize a high-dimensional welding control, the authors have developed the special welding-control microprocessor called welding best electronic engine (Welbee), the single-purpose LSI for the welding control, which is the unique fourth-generation engine dedicated to the welding and inverter controls [10]. By using the Welbee, the operation processing rate can be increased from a conventional micro-order level to a nano-order level, and thereby the control performance of the welding power source can be improved by 64 times higher than that of the first-generation welding power source. This high performance has enabled to sample the welding current and voltage at a super-high speed and thus to monitor/control the complex arc phenomena that could not necessarily be controlled by conventional power sources due to insufficient operation-processing rates.

Digital control methods for the welding current waveform and their performances. *Development of spatter reduction GMA welding process*. The several methods for reducing spatter, typically the controlled bridge transfer (CBT) method [11] that feature less spattering in the short-circuiting current range (up to around 150–180 A) in CO_2 arc welding have been suggested and realized for the low-spatter welding process. On the other hand, from the viewpoint of higher welding efficiency, the low-spatter performance is required also in the globular-transfer current range where the metal transfer is prone to become irregular and unstable. However, the spatter performance of the conventional welding power sources was not enough in the globular-transfer current range (over 200 A).

As shown in Figure 3, in the use of the welding power source equipped with the dedicated welding microprocessor of Welbee, the superimposed pulse current waveform, which consists of periodical changes, is applied immediately after the re-arcing from short-circuiting to regulate the metal transfer. Additionally, the welding current is controlled to be nearly tens of amperes at the moment of shifting from short-circuiting to arcing by means of the high-speed operation processing of the algorithm for detecting the weld pool condition in the last stage of the short-circuiting. The development of this technology for

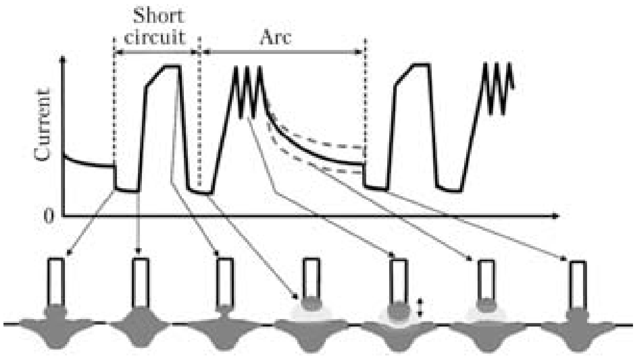


Figure 3. Controlled bridge transfer expanded (CBT expanded) process

controlling the welding current waveform has enabled to reduce spatter even in the current range over 200 A.

Figure 4 shows a comparison of the amounts of spatter in CO_2 arc welding with a Welbee-installed welding power source and a conventional welding power source. The right part of the figure shows typical spattering views and the relative amounts of spatter. In the condition where the amount of spatter is 0.5 g/min or less, only minute particles of spatter are observed. In the condition where the amount of spatter is 1.0 g/min or larger, a mixture of coarse and minute particles of spatter can be observed.

Control for stabilizing the metal transfer in pulsed GMA welding. Table 2 shows examples of the welding-current-waveform control in pulsed GMA welding that have recently been developed by applying the digital control technology [12].

In the pulsed GMA welding of mild steel, the common shielding gas used is an Ar–CO_2 mixture with 20 % CO_2. On the other hand, the CO_2 ratio in the shielding gas mixture often changes depending on the mixing mechanism and the performance of the mixer in cases where the shielding gas is supplied to the welding process line via a concentrated piping system in the workshop. It is known that the metal transfer becomes unstable when the CO_2 ratio exceeds 20 % in the shielding gas, and thereby the one-droplet per pulse transfer becomes impossible to achieve.

With the newly developed pulse-current waveform control, the initial value of a pulsed current is set to be higher than the proper value for 80 % Ar + 20 % CO_2, in order to enhance the constriction of a droplet for detaching from the wire tip even when the CO_2 mixing ratio becomes higher up to 30 %. This control method also features the two-step pulse waveform, which reduces the pulse current to prevent the droplet from becoming larger excessively while maintaining the electromagnetic pinching force to detach the molten droplet formed at the initial stage of the process. In the process of lowering the pulse current to the base current, it is reduced exponentially, not linearly, in order to maintain the electromagnetic pinching force immediately before detaching the molten droplet. Consequently, this process assures a steady metal transfer while preventing the generation of minute particles of spatter that is caused by the residue of molten droplet flown apart from the wire tip as the result of an excessive energy accompanied by the detachment of the droplet.

In the pulsed GMA welding, stainless steel requires the shielding gas with a higher ratio of Ar as compared with mild steel; in general, oxidized gas (O_2 or CO_2) is added at several percent to improve the arc stability. However, even if an Ar-rich shielding gas is used, a stable metal-transfer arc may not be obtained in the pulsed GMA welding of stainless steel because the high viscosity or surface tension of the molten droplet makes it difficult to detach the droplet from the wire tip. With the newly-developed current waveform control, the initial rising rate of a pulsed current is designed to be high so that the electromagnetic pinch force can firmly work on the molten droplet at the initial rise of pulsed current. Additionally, to cope with a lack of electromagnetic pinch force while a pulse current is applied, the pulse current is designed to increase

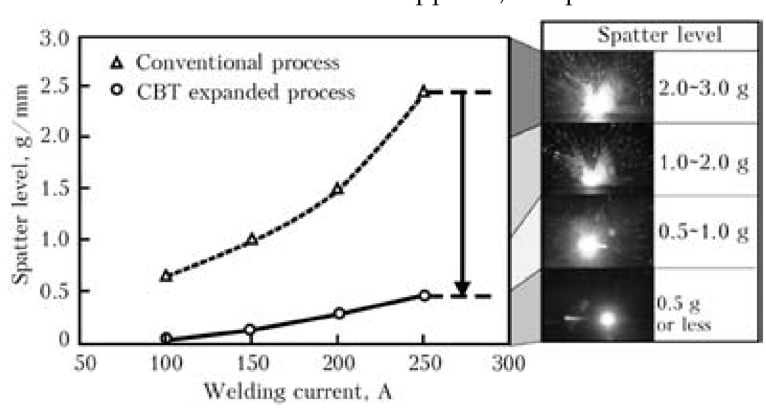
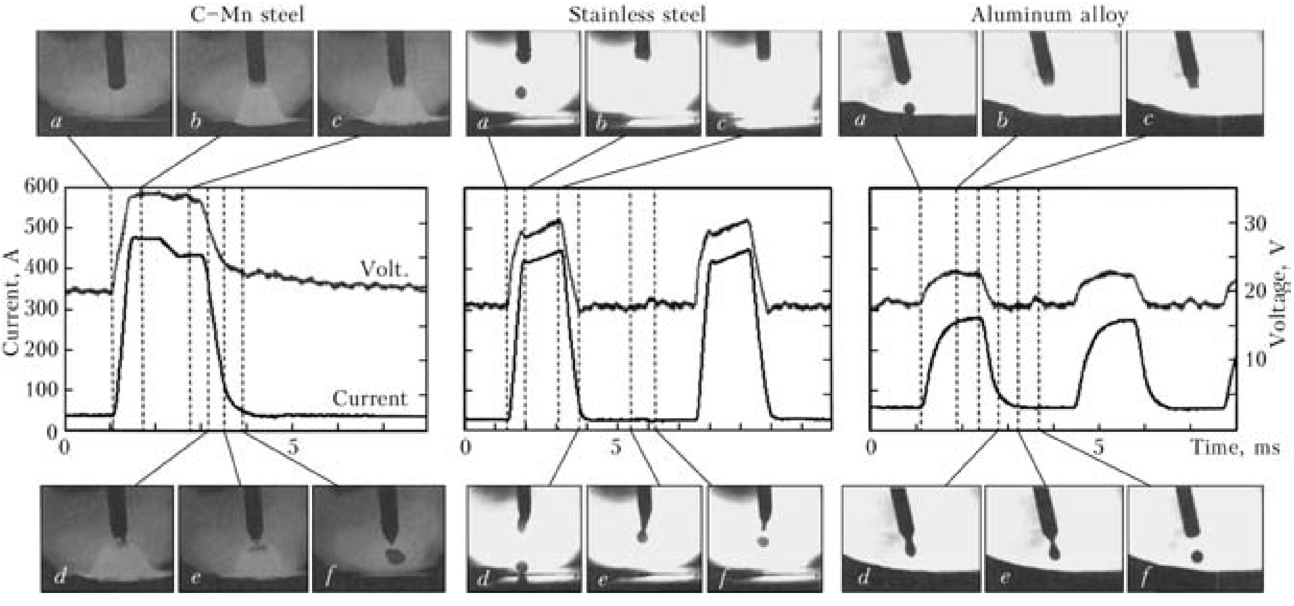


Figure 4. Comparison of spatter level

Table 2. Pulsed wave form type and their metal transfer



gradually after reaching the pulse current, thereby ensuring the sufficient electromagnetic pinch force in accord with the timing of detaching the molten droplet. The process of reducing the pulse current to the base current is the same as the pulse waveform for the pulsed GMA welding of mild steel; i.e., the pulse current is decreased exponentially to prevent the generation of minute-particle spatter caused by the residue of molten droplet flown apart from the wire tip, thereby achieving a steady metal transfer.

In the pulsed GMA welding of aluminum and its alloys, the pulsed-current waveform control must be executed in consideration of the properties that the melting point, viscosity and surface tension of the wire are lower than those of steel wire. Especially, if an excessive pulse peak current is energized to the wire, minute particles of spatter may be generated when the molten droplet detaches from the wire. To solve this problem, the lately-developed current waveform control features the exponentially ascending or descending curves for the rising or falling current waveform between the peak current and the base current. This technology prevents the generation of minute-particle spatter when the molten droplet detaches, thereby obtaining a stable one-pulse one-droplet transfer.

Pulsed GMA welding process with superimposed low-frequency pulse. In 1990, the pulsed GMA welding process with superimposed low-frequency pulse was developed for aluminum and its alloys [13]. In this process, the arc condition is changed cyclically by controlling the output current and voltage with the welding current waveform that features the low-frequency pulse superimposed, for reflecting the vibration of the weld pool, on the medium frequency pulse that controls the metal transfer under a constant wire feed rate.

With this advanced technology, the authors have made suggestions for realizing the GMA weld beads with the regular ripple pattern like TIG weld beads, and for using the weld pool vibration to refine crystal grains and to reduce the susceptibility to solidification cracking [14] as well as to prevent blowholes [15].

However, with mild steel and stainless steel whose melting points are higher, the change in the arc phenomena is not as cyclical as observed with aluminum alloys; thus, the above-mentioned effects could not be achieved.

To overcome this problem, the new pulsed MAG/MIG welding process with superimposed low-frequency pulse has been developed, with which the wire feed speed can be synchronized with the current waveform control, as shown in Figure 5. With this advanced process, the output can dynamically be changed at a low frequency of 5 Hz max for mild steel and stainless steel, and thereby it has become possible to change significantly the arc pressure and wire melting rate.

With this advanced process, a molten pool can cyclically be vibrated. This function enables to remove zinc vapor from the molten pool in the welding of galvanized steel plates, thereby reducing the occurrence of blowholes and pits in the weld metal.

Development of AC-pulsed GMA welding process. Depending on the type of welding structure, some of the welding joints, may be difficult to weld because the root gap is required to be

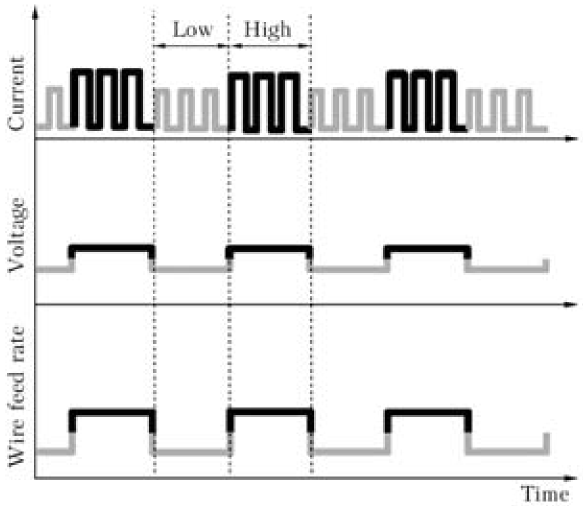


Figure 5. Low-frequency modulated pulsed GMA process

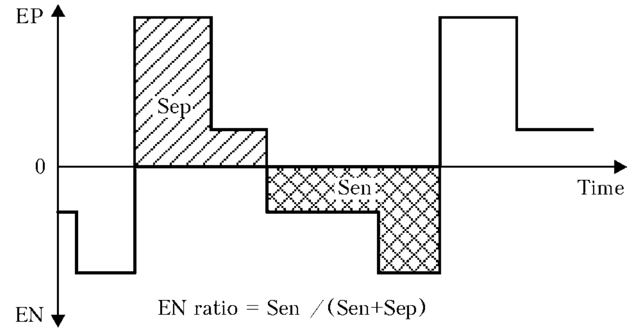


Figure 6. AC pulsed GMA waveform

filled with deposited metal even though the base metal's thermal capacity is small. In the automatic welding of such particular joints, the use of low welding current can prevent burn-through that is caused by excessive heat input; however, it will become difficult to bridge the root gap with deposited metal. Conversely, if the welding current is increased to fill the root gap with deposited metal, excessive heat input may cause burn-through. This problem can be attributed to the nature of the common DC GMA welding process in which the welding current is related directly to the wire melting rate. Therefore, it is significantly difficult to set the proper welding condition in the welding by robots and automatic machines. Even if the proper condition could be set up, it would become difficult to maintain/control that condition due to less robustness.

The AC-pulsed GMA welding process is one of the processes that can solve such welding problems.

Figure 6 shows a welding current waveform in AC-pulsed GMA welding.

In AC-pulsed GMA welding, the ratio of EN polarity current to the average welding current in one pulse cycle is called the EN ratio [16] which can be defined by the equation shown in the figure: EN ratio = Sen/(Sen + Sep).

Figure 7 shows the relation between welding current and wire feed speed as a function of the EN ratio in the use of Al–Mg alloy wire and mild steel wire with a wire diameter of 1.2 mm. As shown in these figures, setting an EN ratio can determine the melting characteristic curve for a particular wire in relation to the melting rate vs. welding current in AC-pulsed GMA welding. Specifically, when comparing the EN ratios at the same welding current, the wire melting rate becomes faster with a higher EN ratio, and slower with a lower EN ratio.

When the wire melting rate is kept constant, a change in the EN ratio affects the welding current; i.e., the welding current decreases with a higher EN ratio, and increases with a lower EN ratio.

Due to these characteristics, changing the EN ratio affects the cross-sectional contour of a weld bead in AC-pulsed GMA welding as shown in Figure 8; i.e., with an increase in the EN ratio, the bead width and penetration decrease, and weld reinforcement increases. This specific feature of the AC-pulsed GMA welding process is

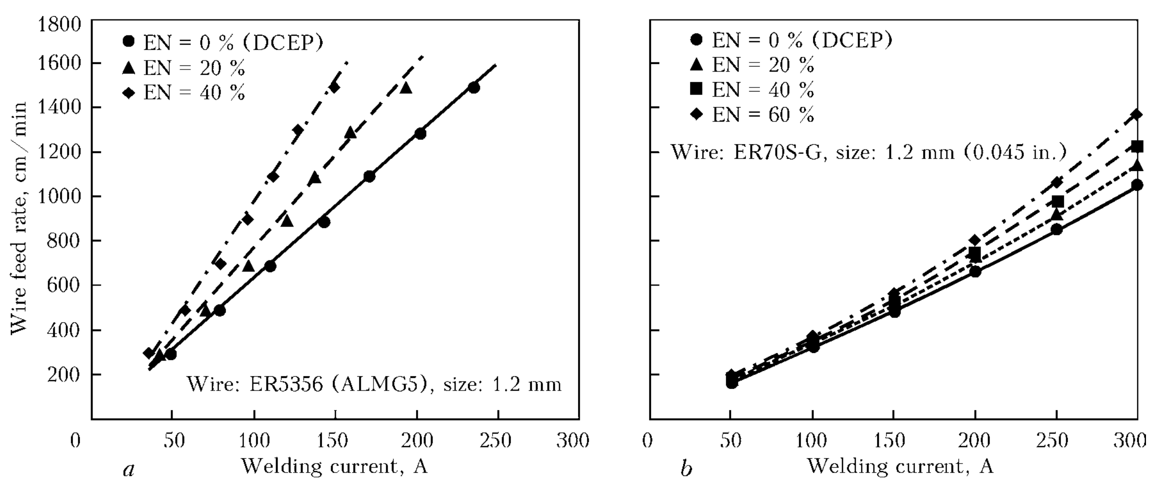


Figure 7. Wire melting characteristic: *a* — aluminium alloy wire; *b* — mild steel wire

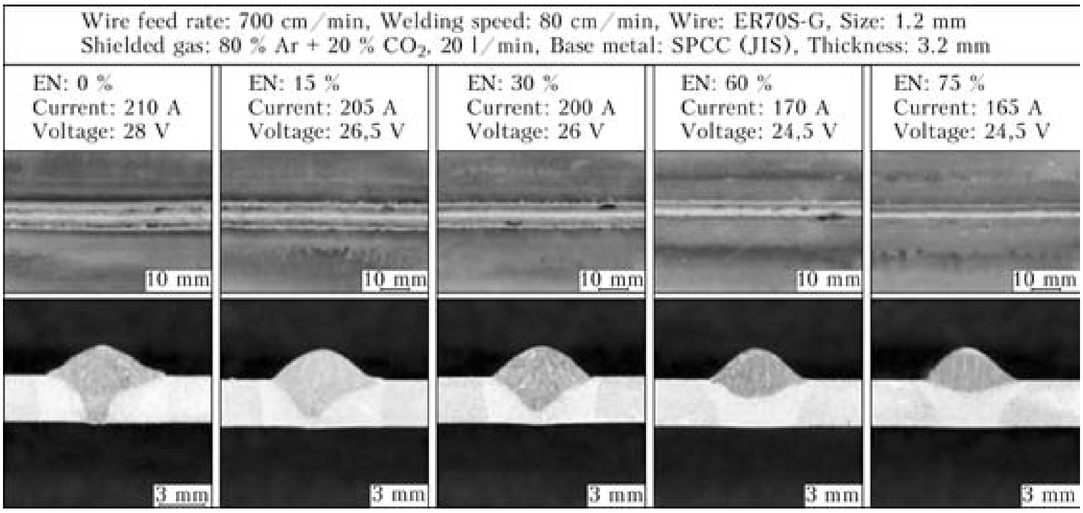


Figure 8. Effect of EN ratio on bead formation

useful in the welding of a welding joint having an excessive gap.

Cold tandem GMA welding. Figure 9 shows the principles of the cold tandem GMA welding process. Specifically, a couple of wires are aligned in tandem along the welding line, and while the leading wire generates a pulse arc, the trailing wire that is not energized is fed into the molten metal produced by the leading arc. In the cold-filler tandem GMA welding process, the filler wire is fed at 5 mm away backwards from the leading arc in the molten pool, unlike the TIG filler welding process in which the filler wire is fed into the molten pool immediately beneath the arc. With this process, the solidification rate of the molten pool becomes faster and thus the prevention of undercut and humped bead can be expected. Because the filler wire is fed into the rear part of the molten pool, the heat capacity of the arc is never drawn by melting the filler wire. This is why the penetration shape is almost not affected by the filler wire fed. In addition, since the preceding arc is kept in perfect spray without short-circuiting, similarly to the conventional pulsed MAG welding process, the generation of spatter is extremely low.

In recent years, thick-plate fabricators tend to use narrow groove joints to get higher welding efficiency. However, the use of a high-efficient welding process in a narrow groove joint may cause the occurrence of a hot crack in the penetrated weld center depending upon the penetration shape. The hot cracking can occur if molten metal does not fill the shrinkage cavity that is formed at the interface (the finally solidified zone) of the columnar structures near the center of a weld during the solidification and shrinkage process. With the cold-filler tandem GMA welding process, the cold filler wire is fed into the molten pool formed by a high-current arc, and hence it can be expected that the molten-metal filling action into the molten pool can be enhanced, thereby preventing the hot cracking.

Figure 10 shows the welding results of the pipe-flange joint of machinery structure steel. In this experiment, welding was started with the pulsed GMA welding process, which was followed in the mid-course by cold-filler tandem GMA welding with the trailing filler wire fed, in order to compare the effect of the filler wire. Consequently, solidification cracking occurred near the center of the bead from the weld start when only pulsed GMA welding was used; by contrast, right after switching to cold-filler tandem GMA welding, the crack propagation was arrested, and thereby the expected effect of the cold filler wire has been confirmed.

Closings and outlooks. The authors have introduced the trends in the development of the GMA welding equipment observed in Japan for the last ten years. The GMA welding equipment has remarkably been improved in tandem with the developments in the power electronics con-

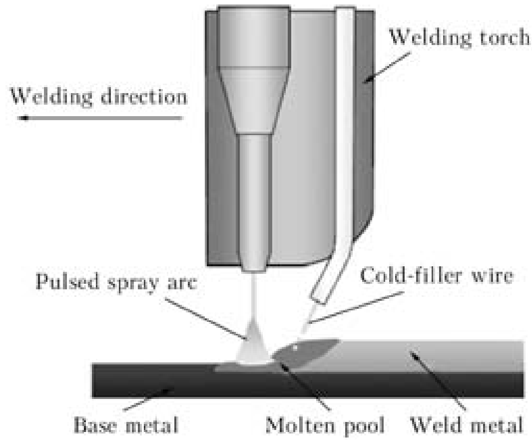


Figure 9. Principle of cold tandem pulsed GMA process

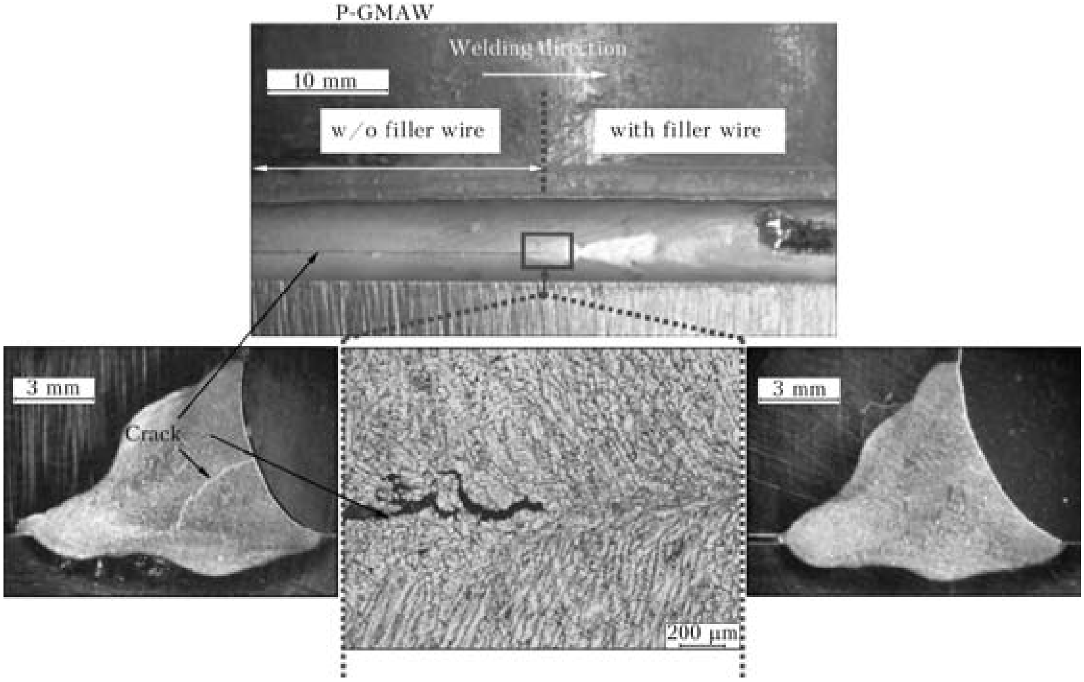


Figure 10. Inhibiting effect of solidification crack propagation by cold tandem pulsed GMAW

trols and elements together with the advancements in various control methodologies. Today, the capacity of microprocessors is also advanced considerably; thus, particular output controls that were hard to realize are becoming possible to practice.

On the other hand, for the fusion welding process like the arc welding process, it is required to handle the phenomena in which solid, liquid and vapor phases can change for a short time. Therefore, in order to accomplish the further advancement/development of the welding equipment, better understanding the physical phenomena centered on the arc phenomena in the welding process will become more vital for the technological step-up in the future.

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Received 01.03.2013

WELDING TODAY AND TOMORROW

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It has been presented the huge changes in the Polish welding engineering which occurred in the last 20 years: in ownership among producers of welding equipment and materials, in investments which have been carried out, in the influence of free market, in the importance of knowledge and in the emerging of the people's own potential. These factors enabled to decrease the distance between the Polish and world welding level. 8 Ref., 5 Tables, 10 Figures.

Keywords: *survey, Polish welding engineering, world welding level, changes in the last years, new factors, eliminating of lag*

While talking about contemporary welding engineering and pondering over its future development, one must also evoke its rich history and refer to its considerable achievements in earlier days, in particular, in the interwar time (1918–1939) as well as during the forty years that followed (1945–1985).

The interwar period witnessed the construction of the world's first fully welded road bridge on the river Sludwia near Lowicz in Poland in 1929 (Figure 1). The bridge has been in its place ever since in spite of wear and tear and destruction caused by the war.

In the interwar period the first buildings (tall buildings as well as exhibition and production halls) were constructed on the basis of welded steelwork. The production works manufacturing welded structure were set up in numerous existing steelworks, which produced considerable amounts of structural steel, in the region of Silesia. Although the production plants of welded steelwork were relatively small, the number of produced structures was imposing. Even today's design engineers and production engineers would not feel ashamed of some of the solutions applied then. It should be also emphasised that many constructions came into being within a very short time.

The post-war period in Poland was the time of rebuilding the country after the ravages of war and starting up numerous industrial plants. In that period the amount of produced structural steel was colossal. It was connected practically with all fields of regenerating civil life as well as rebuilding and developing industry. Steelworks, coal mines, power stations, shipyards, chemical plants are just examples of the biggest consumers of welded steelwork.

Remembering and appreciating «yesterday's» achievements, one must nevertheless admit that it has been the last two decades of political, economic and commercial transformations in Poland, Europe and the world that have had the greatest impact on the «today» of Polish welding engineering.

The factors which made it possible to decrease or even eliminate the gap between the Polish and world's welding engineering are the privatisation among manufacturers of welding materials and equipment as well as manufacturers of welded products and structures, all kinds of investments, free-market awareness, access to knowledge as well as the possibility to develop and improve one's own skills and abilities.

Figure 1. The world's first fully welded road bridge and commemorative plaque affixed by the American Welding Association

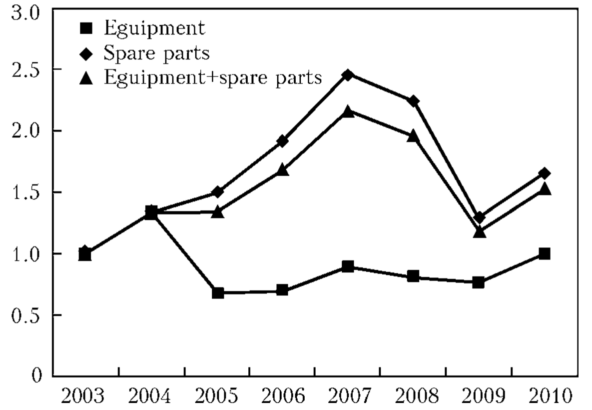

Figure 2. Dynamics of sales of domestic welding equipment in the years 2003–2010

Today's Polish welding engineering has a potential which lays the strong foundations for the welding engineering of «tomorrow».

The image of Polish welding engineering is created by the following:

- manufacturers and distributors of welding materials and equipment;
- applied welding technologies and level of their automation;
- welding sector personnel;
- users of welding technologies;
- scientific and research establishments.

Manufacturers of welding materials and equipment. Privatisation of domestic manufacturers of welding materials and equipment by such companies as ESAB and LINCOLN has opened the world's market (through their perfectly organised distribution networks).

The most fundamental issue now is the access to new manufacturing techniques and technologies. They usually require high financial outlays for research and industrial applications. Finding an investor in Poland is no easy task. Thanks to the investments made by foreign companies the market sector of welding materials and equipment has considerably strengthened its position. A recent decision of the ESAB company to move the production of welding equipment from Sweden to the city of Opole seems only to confirm this trend (Opole is going to have the biggest production plant of ESAB welding equipment in Europe). Also the investments made by the LINCOLN company and its subsidiaries in the scope of production of flux-cored wires or welding torches. The gas companies that have located their investments in Poland include LINDE, MESSER, AIR LIQUIDE and AIR PRODUCT.

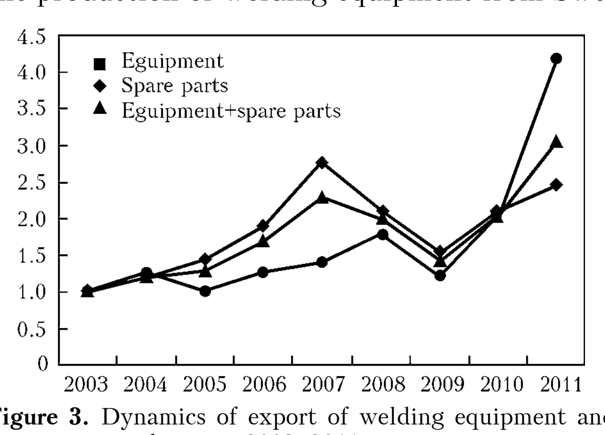

Figure 3. Dynamics of export of welding equipment and spare parts in the years 2003–2011

It should be clearly emphasised, however, that apart from large international companies there are over a dozen Polish big and small companies manufacturing welding materials and equipment, such as ASPA, ZBUS, ECKERT, ZASO, ELKO, MULTIMET, METALWELD, TECHNIKA SPAWALNICZA and others. These manufacturers supplement the large companies' offer with specialist materials and equipment for welding engineering.

Over two thousand distributors and servicing points in Poland provide their services to the customers of welding engineering companies. Thanks to investments made, privatisation process and organizational changes, there has been a steady growth in the potential and competitiveness of Polish welding engineering on the global markets. This can be seen in the figures relating to the dynamics of the market of welding materials and equipment.

The year 2003 was adopted as the basis for the analysis of the market dynamics, of both welding materials and equipment. That was the year of the sale growth after the economic slump in the years 2000–2002.

After the period of a boom in the economy in the years 2003–2007 (Figure 2 and Figure 3) the impact of the world's crisis on the domestic market of welding equipment became visible. The total production of equipment and spare parts sold in 2007 was twice as much as in the year of 2003, whereas in 2009 it approached the level of the year 2003. The years 2010–2011 saw the recovery of the economy. The total value of the export of equipment and spare in 2011 exceeded the level of the year 2007, which was a very good year for the market of welding engineering.

Thanks to a perfectly developed distribution network, including networks of the ESAB and LINCOLN companies, the equipment manufactured in Poland is exported to over 100 countries all over the world. The biggest number of devices is exported to Belgium (16 %), Russia (15.3 %), USA (9.9 %) and Germany (7 %).

The dynamics of the market of electrodes and flux-cored wires shows that there has been a considerable export growth in both fields. The export of covered electrodes in the years 2003–2010 increased over 10 times, whereas that of flux-cored wires over 7 times (Figures 4 and 5). Similarly as was the case with equipment, the world's crisis of 2009 caused a decrease in export of covered electrodes and of flux-cored wires. However, the domestic use of covered electrodes remained at the level of the year 2003. The use of flux-cored wires was gradually growing. In 2007 it was over 3 times greater, and in 2010 it was twice as high as in the year 2003 (Figure 5).

The dynamics of import of welding equipment was either stable or of a declining character. In the years 2003–2010 the value of import did not exceed the level of the year 2003. The highest activity of the manufacturers of welded products and steelwork in the purchase of new welding equipment took place in the years 2007–2008. It resulted, among other things, from a long and arduous effort to build the financial stability of the companies.

The import of welding materials and equipment has taken place in the past and today, and what should be emphasized, from various countries. In 2011 Poland's most important partners in the scope of the purchase of welding equipment were Germany 28.8 % as well as China and Italy with a respective share of 15.3 % and 14.3 % of the total purchase value.

The greatest import of electrodes as far as the mass is concerned has come from Portugal, Hungary and China, whereas electrodes of a relatively higher price and quality have been imported from Sweden, Germany and Holland.

The import of flux-cored wires from China in 2011 was comparable in terms of quantity with the import from Germany. However, the quality of German wires was 2.5 times higher, which indicates their better quality and specialist properties.

Analysing the structure of the total use of weld metals in Poland in 2010, it was possible to observe that the weld deposit coming from solid wires (MIG/MAG) constituted approximately 53 %, from flux-cored wires (FCW) approximately 20 %, whereas from covered electrodes (MMA) and from welding consumables for submerged arc welding (SAW) 18 and 9 % respectively. Both the increase in the use of flux-cored wires and the declining tendency in the use of covered electrodes follow the tendency taking place in developed countries, where in the years 1976–2004 the participation of weld deposit obtained during manual welding with covered electrodes decreased from 51 to 12 % in Western

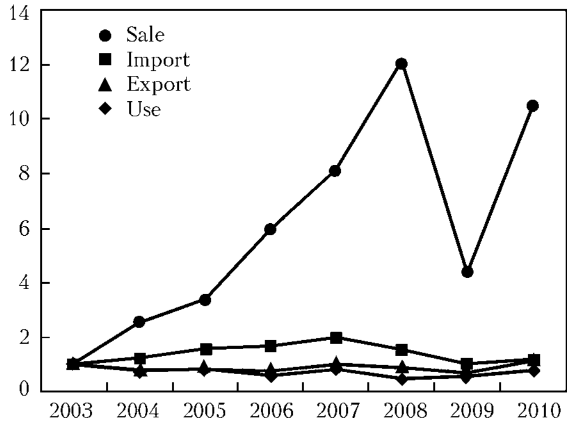

Figure 4. Dynamics of the market of covered electrodes in the years 2003–2011 acc. to mass

Europe, from 49 to 12 % in the USA and from 70 to 13 % in Japan.

Applied welding technologies and level of their automation. General trends in the scope of welding technologies applied in Poland do not diverge from those in the developed countries in Europe and in the world. In the general hierarchy of applied methods, manual welding with covered electrodes is relatively rarely applied, while the application of flux-cored wires and semi-automatic MIG/MAG welding is on the increase. However, nowadays the state-of-the-art methods and cutting-edge welding technologies are laser welding and cutting, hybrid welding, electron welding, welding with several wires, low-energy processes as well as automatic and robotised welding.

All of the above-mentioned processes are known and applied in Poland, however, the scope of their use is different from the one observed in the developed countries. The world's production of industrial lasers in 2008 amounted to 41700 units. About 36 % of this number, i.e. over 15000 items were installed in Europe. If one assumes that 22 % of lasers were used for cutting and 12 % for welding, then 5100 lasers were used in welding processes in Europe solely in the year 2008. According to estimates, around 2000 units

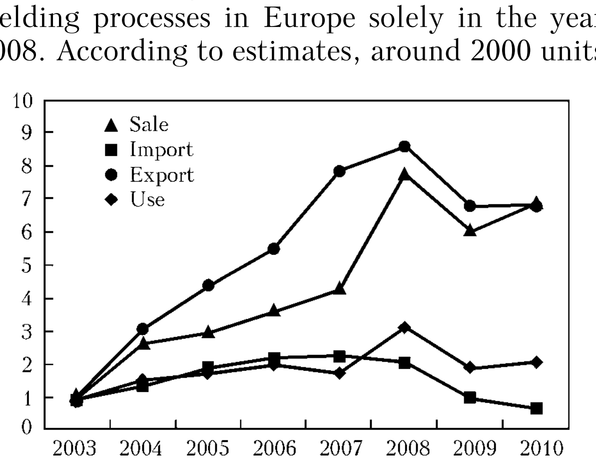

Figure 5. Dynamics of the market of flux-cored wires in the years 2003–2011 acc. to mass

Table 1. Welding robots installed in different countries in 2010

Country	Number of pcs	Country	Number of pcs
China	8000	India	446
Germany	4129	Slovakia	396
North America	3883	Brazil	246
South Korea	3800	Great Britain	197
Japan	3609	Poland	171
Spain	563	Portugal	131
France	496	Russia	115

Table 2. The total number of the international diplomas acquired by the welding personnel in the years 1999–2011 was 2.400

Number of diplomas	IWE	IWT	IWP	IWS	IW	IWIP
	1.418	200	150	362	31	239

Table 3. The total number of European diplomas acquired by the welding personnel in the years 1997–2011 was 1.734

Number of diplomas	EWE	EWT	EWP	EWS	EW
	1.108	179	158	72	91

were installed in Poland, including several dozen intended for welding. Hybrid welding is already a subject of research and experimental testing. There are some single industrial applications of hybrid welding but still a lot needs to be done in this area.

A similar situation is in the case of robotisation of welding. There is over a million of robots installed all over the world, with 30 % of this number being made up by welding robots.

Among welding robots a dominating position is taken by robots for welding and fusion welding, whereas robots for brazing and, in particular for laser welding, have prospects of development.

As the measure of robotisation level one uses the number of robots per 10 thousand people employed in all industries or in the automotive industry. It is estimated that in the world there are approximately 50 robots per 10 thousand employees in all industries. However, in such countries as Japan and Germany there are respectively 1436 and 1130 robots per 10 thousand workers employed in the automotive industry and 191 and 134 robots in all industries. In Poland in 2010 there were 5158 robots installed in all industries, with 2559 robots used in the automotive industry. Therefore, there are 19 robots per 10 thousand employees in all industries and approximately 176 robots per 10 thousand employees in the automotive industry.

The number of welding robots installed annually in different countries is worth emphasising. The potentate is China where in the year 2010 eight thousand welding robots were installed. In Germany, North America, S. Korea and Japan this number fluctuates around four thousand, whereas Poland, with 171 robots, takes one of the last positions in terms of the number of installed welding robots (Table 1).

Welding sector personnel. The personnel employed in the welding sector is one of the greatest assets of Poland's welding engineering; this being due to the level and organisation of educational processes, practical training and experience in manufacturing critically important structures by domestic producers. The international system of educating welding personnel implemented by Instytut Spawalnictwa enables obtaining international certificates (Table 2) and European diplomas (Table 3). Instytut Spawalnictwa collaborates with the European Welding Federation as well as the International Institute of Welding and contributes significantly to their work.

Vocational training is run in Poland by approximately 400 centres supervised by Instytut Spawalnictwa. Several dozen thousand documents are issued every year (Table 4).

It is estimated that approximately 130–150 thousand people are involved in work for the welding engineering sector, including 60–80 thousand of welders.

Users of welding technologies. Depending on the economic situation, in Poland, in over 100 industrial sectors there are between 6.5 and 7 thousand companies using welding and related technologies in production processes. Such companies create about 50 % of the added value. Poland comes second in Europe as far as the quantity of steelwork production is concerned (1.35 m tons). There is also a high share of export in the structure of production. In 2010 export amounted to 630 thousand tons, while import reached 195 thousand tons (Figure 6). All this is a clear indication of the strong position of companies connected with the welding engineering sector.

Table 4. Documents issued every year

	2004	2005	2006	2007	2008	2009	2010	2011
Welders Qualification Test Certificates	20.566	22.487	34.576	42.423	43.789	46.199	44.454	42.499
Welder's Books	8.740	10.580	15.474	21.524	17.604	14.736	13.918	13.662

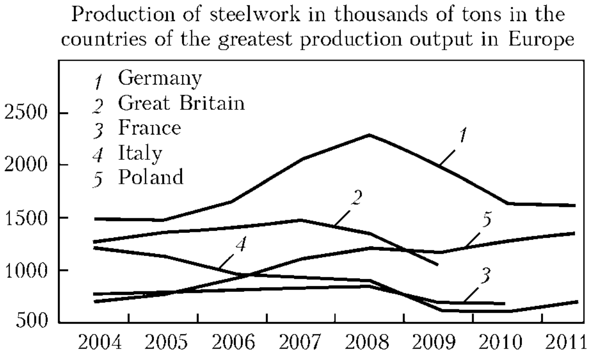

Figure 6. Production of steelwork in thousands of tons in the countries of the greatest production output in Europe

Domestic manufacturers make the most reliable and responsible welded steelwork for power engineering, aviation, building engineering, petrochemical sector, gas engineering, transport, automotive industry, ship building, etc. Their export and price relations show Poland as a country with a very competitive offer.

What is insufficient, however, is the outlays incurred by industrial companies for innovative activity. The companies allocate over 80 % of their financial resources for purchasing equipment and just merely 10 % for research and development.

Scientific and research potential. The expert institutions dealing with welding engineering in Poland are Instytut Spawalnictwa (the biggest establishment in Poland, with 165 employees), chairs or departments at 16 universities (employing from several to a dozen or so workers), the Polish Academy of Sciences, some research institutes as well as large industrial plants with their testing and research facilities. Industrial plants with a foreign capital usually carry out their research in their own scientific centres, sadly, outside Poland.

For the past 20 years the laboratories conducting research for the welding engineering sector have been equipped with the state-of-the-art lasers, robotised welding equipment and modern testing machines.

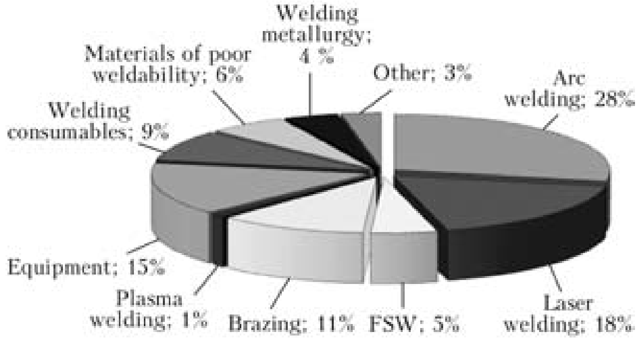

Figure 7. Structure of research projects financed from the budget in the field of welding engineering in Poland in the years 2000–2007

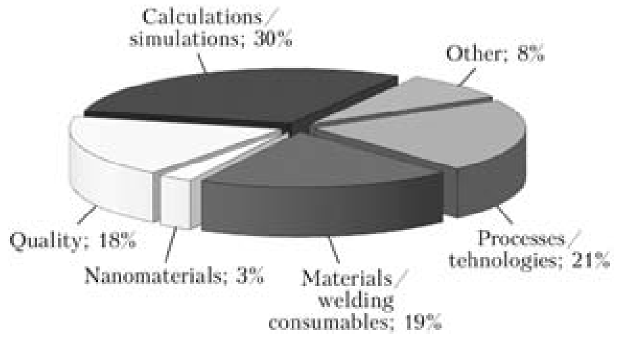

Figure 8. Structure of outlays for research projects financed from the budget in welding engineering in Poland in the years 2007–2011 (acc. to value)

Table 5 presents financial outlays for research projects in welding engineering financed from the budgetary resources.

The structure of research issues and financial outlays for research shows that despite limited outlays the scope of the research carried out in Poland has covered the majority of problems essential to modern welding engineering, such as laser welding (including hybrid welding), plasma welding, welding (including FSW), materials of poor weldability, nanomaterials, calculations and simulations of processes etc. (Figures 7 and 8).

The assets of today's welding engineering:

• powerful and quickly developing production and distribution facilities of welding materials and equipment;

Table 5. Financial outlays for research projects in welding engineering

Description	Projects financed by MNiSW in the following years				NCBR projects	Developmental projects
	2002–2007		2008–2010		2010	Years 2007–2008
	Own	Superv.	Own	Superv.	Initech	
Number of projects	28	10	21	9	3	4
Financial outlays in thousands PLN	6567.9	414.7	6325.3	463.1	10877.0	2091.0
Average outlays in thousands PLN per 1 project	234.6	41.5	301.2	51.4	3625.7	522.7

Note. MNiSW – Ministry of Science and Higher EducationNCBR – National Centre for Research and Development. Superv. – Supervisory. Initech – Innovative Technology.

• highly skilled welding personnel thanks to the international system of vocational education and training as well as owing to experience gained at production of reliable steelwork of critical importance;

• welding technologies hierarchy applied in accordance with the world's trends;

• great potential and production capacity of the manufacturers of welded products and steelwork;

• powerful research and testing facilities and experienced researchers as well as the range of research-related issues taking into consideration the world's latest trends.

Welding of the future. Welding engineering of the future will depend on research conditioning the development of structural materials and technologies to join them, educational and vocational background of the welding personnel, the level of innovation at companies and a general economic situation.

Research in the area of structural materials. The research of materials processed by means of welding technologies will include:

• parent metals: steel, aluminium, magnesium and plastics;

• new materials: titanium and its alloys, composite and ceramic materials, multi-materials;

• materials of the future — nanometals.

As can be seen in Figure 9, the production of steel is four times higher than that of other structural materials. For this reason the use of steel is and, in the nearest future, will continue be a fundamental indicator of the condition and development of individual industrial sectors, including welding engineering.

The research related to the development of structural materials has been addressed in many publications and research programmes such as European Strategic Energy Technology Plan (referred to as the SET Plan) developed by the Polish Steel Technology Platform (Polska Platforma Technologiczna Stali) as well as the programme «Horizon 2020» being prepared by the European Union. The latter programme is supposed to be in operation from 2014 to 2020 and provide approximately 80 bn PLN to finance European research and innovations.

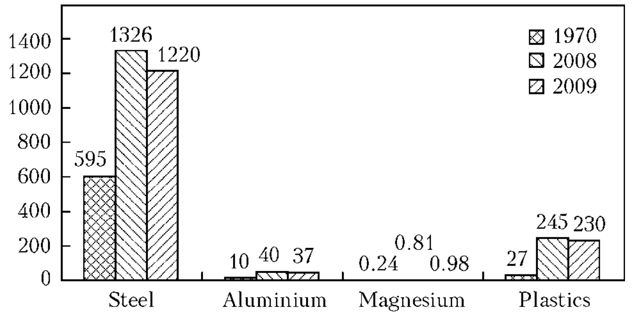

Figure 9. World's production of major structural materials

Welding technology development. New structural materials of poor weldability pose a real challenge for welding engineers. These include:

• materials resistant to high temperature;

• multi-materials in the form of sheets, shapes and casts;

• high-strength steels + soft steels, aluminium;

• steel + carbon fibre reinforced plastics (CFRP);

Technologies of the future are:

• laser, hybrid and electron beam welding;

• remote controlled welding using concentrated energy;

• always relevant electric arc welding: Cold Metal Transfer, STT (Surface Tension Transfer), Cold Arc, SCW (Synergic Cold Wire), two-arc MAG welding, submerged arc welding with multiple electrodes and thin wires as well as TIME methods.

The growth in the productivity and quality of welded joints is conditioned by the automation and robotisation of high-efficiency welding processes as well as by computerised control of welding processes, first of all due to high current parameters and welding rate values.

Innovative solutions. «Being innovative» is the ability to create and use in practice new and effective solutions which have become feasible owing to research and experience gained during production.

Effective solutions bring the following advantages:

• increase in quality and efficiency;

• reduction of costs;

• reliability and competitiveness of manufactured welded products and structures.

Innovation is the most effective method to enjoy competitive and economic success. «Innovation means knowledge turned into money». All too often one can see only expenditure related to the implementation of new solutions. In fact, costs are borne only once, whereas benefits keep coming in for years.

Innovation obviously does cost, and poses a great problem in countries like Poland. Welding engineering companies have been arduously building their financial stability, investing in fixed assets, building or renovating production halls, purchasing welding machinery and equipment. This phenomenon is very positive and important as these areas have been neglected for many years. However, the foregoing is insufficient to boost efficiency and competitiveness. The future and competitiveness of Polish welding engineering will, to a much greater extent, depend on the companies' activity in the field of innovation.

Influence of economic situation on Polish welding engineering. The globalising economy increases international competition. If the welding engineering industry is to play an important role in it, it will have to face up to this challenge. It is difficult, though, to predict what shape the economy will take in Poland and in the world.

Welding engineering needs a good economic situation in sectors being the main users of welding techniques i.e. metal products (for power engineering), building engineering, automotive and transport industries (including shipbuilding), equipment and machinery, renovation and repair (Figure 10).

Examples of investments which may positively influence the economic situation of the welding industry in the domestic market.

1. The construction of the north-south gas pipeline is due to begin in 2014. It will connect the terminal in the city of Swinoujscie with gas distribution grids in the Czech Republic, Slovakia, Ukraine and other south-European countries. The pipeline is going to be 2000 km long and its construction is to be completed in 2020. Parallel to the above-mentioned investment, there are plans made for the Odessa-Brody-Gdansk pipeline.

2. According the document «Power Engineering Policy for Poland until 2030» approved by the Cabinet, the power engineering sector is going to be the driving force for the development of Polish economy (including welding engineering sector). One of the factors affecting the development of power engineering is the requirements issued by the European Union in relation to the reduction of CO_2 emissions, making it necessary to modernise the existing power units and transmission grids as well as to build new ones, diversify Poland's power generation by building nuclear power plants and implementing renewable energy solutions connected with wind, water, solar or biofuels. All the investments connected with the excavation of shale gas will also be of importance to the welding engineering sector.

3. All the above-mentioned changes will not be possible without new technologies and solutions in welding engineering.

4. The prospects of the development of wind power engineering: at the premises of one of Polish shipyards («Gryfia») a modern «off-shore» unit is being built. It is a joint venture of three companies: German Bilfinger Berger, Gdynia's Shipyard's «Crist» and MARS Closed-end Investment Fund (belonging to ARP — Industrial Development Agency). The target production is to bring 80,000 ton of steelwork making up foundations for off-shore wind turbines, with the main customers being German and British companies.

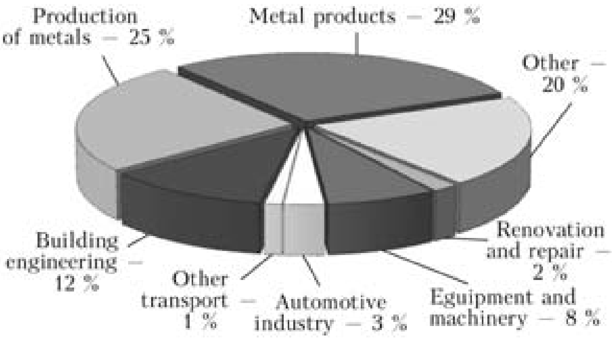

Figure 10. Structure of the use of rolled goods in Poland by sectors related to welding engineering in 2010

5. Gdansk Shipyard has started the production of wind turbines. The target production aims at 300 turbines annually making the shipyard the biggest manufacturer of off-shore wind turbines in Europe.

6. In Goleniow Dutch Glasfiber has set up a plant manufacturing blades for wind power plants.

7. As many as 32 application forms have been submitted to Poland's authorities requesting permission to locate off-shore wind farms.

8. There is a slowdown in the building sector. However, taking into account the needs of the whole infrastructure and planned subsidies from the European Union funds, the building sector still has a chance to favour the development of the welding engineering industry.

9. Planned investments in renewable sources of energy, waste incineration plants, railway sector and further investment in road infrastructure bode well for the welding sector.

10. There has been 3 bn PLN allocated for the modernisation of railway lines so far but this amount will be probably increased to about 10 bn PLN.

11. The automotive and aviation sectors are the driving force for the progress in welding engineering. The share of the automotive sector in creating the added value constitutes 5 % of the general added value of the industry. This is far less than in developed countries but there is some success in this area too.

12. Poland is a number-one manufacturer of buses in Europe.

13. The aviation industry in Poland has numerous relations with the world's aviation companies. The companies that have opened their branches in Poland include Meyer Tool — an

American manufacturer of spare parts for aviation industry, Sandvik — a Swedish producer of cutting tools, acid-resistant steel, electroresistant materials and conveyor belts, Pratt&Whitney Canada — the world's leader in the production of engines, Vac Aero International Canada. At present, most of the companies in this sector belongs to foreign investors. The aviation industry in Poland is represented by the association «Dolina Lotnicza» («Aviation Valley») which encompasses 77 companies employing 22 thousand engineers and technicians.

Conclusions

Assets of contemporary welding engineering:

• reliable production and distribution base of welding materials and equipment;

• welding personnel's high qualifications and extensive experience in production;

• structure/hierarchy of applied welding technologies consistent with the world's trends;

• big potential and manufacturing capacity of the manufacturers of welded products and steelwork;

• excellent research and testing facilities as well as experienced researchers;

• broad scope of research taking into account the world's trends.

Weaknesses of contemporary welding engineering:

• inadequate level of automation and robotisation;

• insufficient application scope of the latest technologies;

• inadequate participation of companies in financing innovative solutions;

• too low outlays for R&D and too low share of R&D in innovative activity.

The future of welding engineering will depend on:

• research conditioning the development of structural materials and technologies of joining them;

• level of welding personnel;

• innovative approach of companies;

• general economic situation.

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Received 07.03.2013

ADVANCED INFORMATIVE AUTOMATED SYSTEMS OF ACOUSTIC CONTROL OF WELDING

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Advanced domestic and foreign high-information types of equipment for acoustic testing of pipeline welded joints are considered. Their performance capabilities and disadvantages are noted. The advantages of complex scanner, realizing ultrasonic, eddy-current and visual methods of testing and developed by ETC «Welding and Testing» together with «Molniya» enterprise, were described. Given are the examples of application of AVGUR system as well as ASBAT portable device, which passed interdepartmental testing and were implemented at OJSC Gazprom for testing of welded joints in nuclear-power engineering. 1 Table, 11 Figures.

Keywords: *acoustic testing, pipeline welded joints, scanner-flaw-detector, characteristics of testing system, portable device, head wave*

Significance of non-destructive methods of testing is sufficiently high due to large depreciation (more than 65 %) of processing equipment and necessity of reliable diagnostics of objects being constructed.

Cost of testing operations in manufacture of separate products of military-industrial complex in USA achieves 25–35 % from the total product cost. These costs make 10–12 % in building industry. The costs of testing and diagnostics in Russia are 15–20 time lower due to what number of accidents on different designation objects is an order higher than in the West.

Necessity in a safe high-information equipment is in particular relevant for a fuel-energy complex where the accidents are connected with large economic losses as well as disastrous effects.

Acoustic methods have found the largest application among all the variety of diagnostic methods during manufacture, building and operation of structures. Avtokon-AR-MGTU automated ultrasonic scanner-flaw-detectors are the most efficient means for weld quality testing in evaluation of technical state of main pipelines, gasholders and tanks.

The self-sufficient robotic system represents itself a displacement mechanism carrying a 32-channel ultrasonic flaw-detector with controlling processor and acoustic system, consisting of two 16-element combined probes (IP). The latter realizes a testing technology using phased arrays with beam swinging aperture in 40° range at 8 MHz frequency (Figure 1).

Two other 16-element probes, operating in separate mode, provide a testing technology applying Time-of-Flight Diffraction (TOFD) method (Figure 2, *a*).

The signals scattered on defect edges are registered and recorded during TOFD and B-scan is displayed on the screen (Figure 2, *b*).

The system is installed on the object of testing and moved along the welded joint automatically tracking it without any additional devices. A scanning mechanism is held on the pipe surface by constant magnets embedded in the wheels. The unit is small-size, easy in operation and serviced by two operators.

Comparison characteristics of robotic systems are given in a Table.

Domestic device, together with indicated above advantages (Table), allows testing the products of any shape (flat sheets, tanks, gasholders, etc.). Figure 3 shows an example of flaw detection of the circumferential pipe butt joints.

It should be noted that the best available foreign analog Pipe WIZARD-PA (RTD company) can only test circumferential butt joints (Figure 4) on the main pipelines.

Existing ultrasonic scanners Avtokon-AR-MGTU, «Sonet», USD-60, etc. do not allow de-

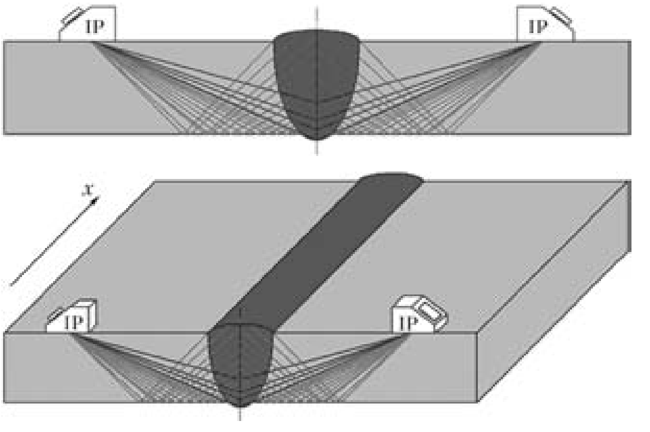


Figure 1. Acoustic system of scanner-flaw-detector Avtokon-AR-MGTU with phased arrays

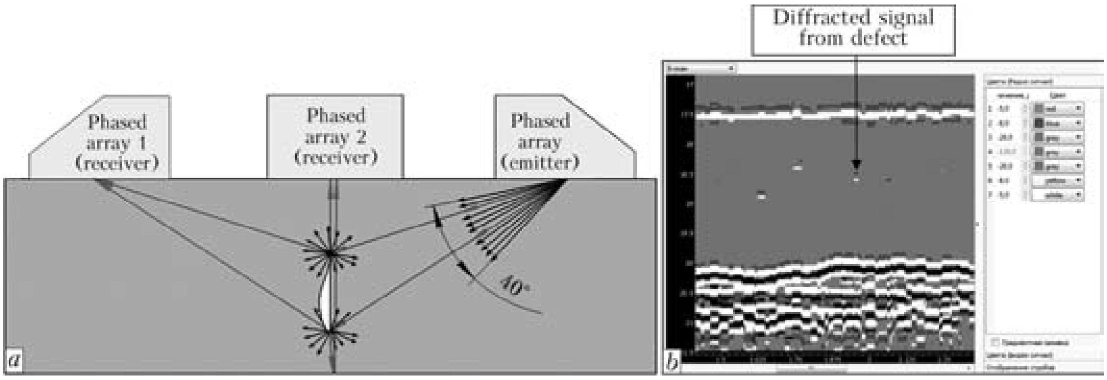


Figure 2. Acoustic system of scanner-flaw-detector Avtokon-AR-MGTU with phased array of «duet» type (*a*) and diffracted signals (*b*)

tecting the stress-corrosion damages in the main pipelines with high probability level. Thus, ETC «Welding and Testing» at the N.E. Bauman MSTU together with SPC «Molniya» developed a complex scanner realizing ultrasonic, eddy-current and visual methods of testing (Figure 5, *a*) for elimination of indicated disadvantage and increase of surface and internal defect detectability. It is designed for testing of 720–1420 mm diameter pipelines with wall thickness up to 35 mm at −40 to +40 °C temperature. Speed is up to 3 m/min and width of scanning zone makes 280 mm per one revolution at movement on helical line. The results of diagnostics are represented in a form of scanogram (Figure 5, *b*)

AVGUR 5.2 systems (Figure 6), developed at SPO «Ekho+», are the most efficient during testing of quality of butt welded joints in pipelines of primary coolant circuit of WWR- 1000 reactor.

Large thickness (72 mm) and presence of a fillet from which cracks mostly initiate in service, are typical for these joints. AVGUR 5.2 system finds occurring defects with high reliability and allows identifying their sizes and configuration (Figure 7).

AVGUR 5.2 system after insignificant rekitting is successfully used for testing of bends of pipelines of WWR-1000 primary coolant circuit (Figure 8).

Information about form, size and coordinates of the defects is not always enough for evaluation of object serviceability. Presence of residual stresses in different elements of structures, in particular in defect zone, makes a significant effect on a stress-strain state level.

There is a great number of devices for evaluation of residual stresses, effect of which is based

Comparison characteristics of robotic testing systems Pipe WIZARD-PA (RD TECH™) and Avtokon-AR MGTU

Parameter or characteristic	Pipe WIZARD-PA	Avtokon-AR MGTU	Note
Self-sufficiency	Within the length of communication cable of mobile block and hose for couplant feeding	Complete	At pipeline testing the main block of Pipe WIZARD-PA should be mounted on a car and length of the cable and hose ≥20 m
Scanning method	Automatic, along a guide, mounted on the weld	Automatic, without additional devices	AVTOKON-AR-MGTU is equipped with a sensor for tracking weld reinforcment bead or flexible strip
Weight, kg	More than 50 kg without the weight of external computer, couplant tank, hoses and cables	≤18	Pipe WIZARD-PA is not portable
Range of controlled thicknesses of pipeline base metal, mm	7–32	6–35 (at acoustic block replacement)	Mainly, pipeline base metal thickness ≥8–30 mm
Range of working temperatures, °C	−15–+30	−40–+ 50	Testing mostly is carried out at negative temperatures
Main testing results	Defect detection, determination of their location and measurement of conditional dimensions	Defect detection, determination of their location and measurement of conditional dimensions	–
Function of acoustic coupling monitoring	Yes (separate transducer by reflection from pipe inner surface)	Yes (at each starting of any channel without application of additional equipment)	–
Testing scope	Circumferential welds	Circumferential and longitudinal welds, pipe body	–

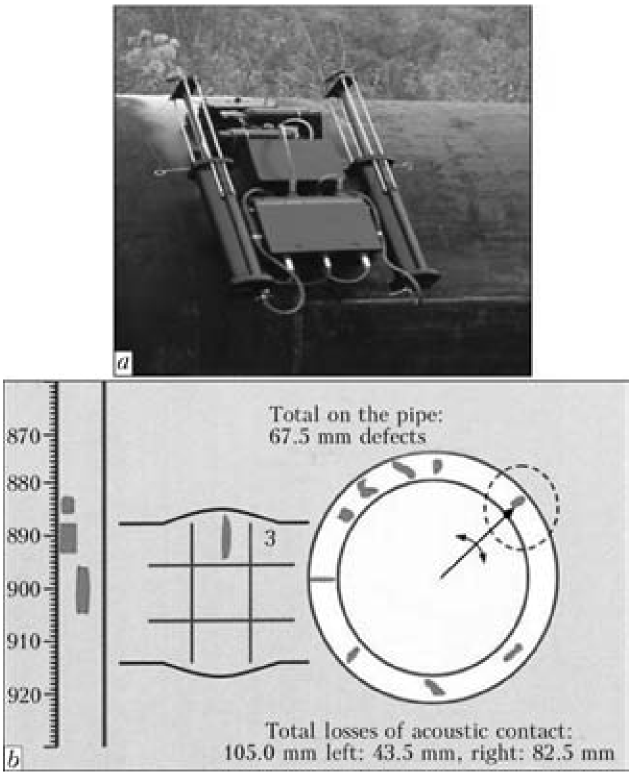


Figure 3. Scanner-flaw-detector Avtokon-AR-MGTU (*a*) and representation of testing results on monitor screen (*b*)

on measurement of different characteristics of magnetic, electromagnetic or ultrasonic fields. Low measurement accuracy (20–25 %) is their common disadvantage. LZM-USJzfp unit (German Institute for Non-Destructive Testing) is the most perfect among the well-known systems for measurement of internal stresses. Its principle of operation is based on measurement of transverse

Figure 4. Pipe WIZARD-PA scanner

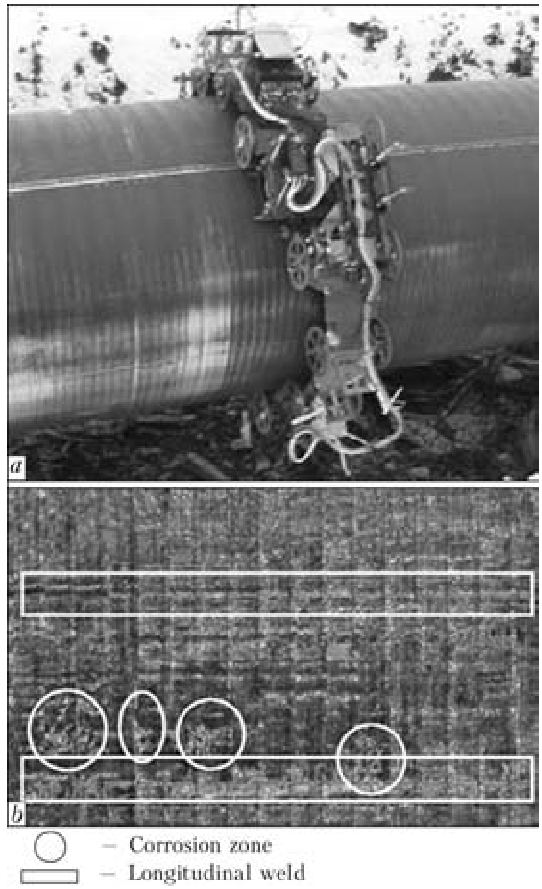


Figure 5. Automated complex system for testing of main pipelines (*a*) and scanogram of defects (*b*)

velocities of US-waves in mutually perpendicular direction. At that excitation of SH-waves is performed by EMA-transducers. This system allows measuring only uniaxially-stressed state with

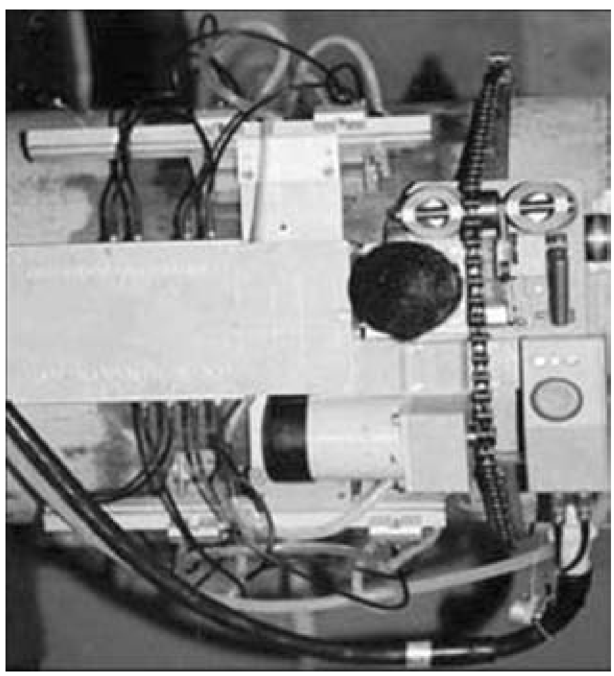


Figure 6. System AVGUR 5.2 for automated ultrasonic testing of circumferential butt welded joints of pipelines of WWR-1000 reactor primary coolant circuit

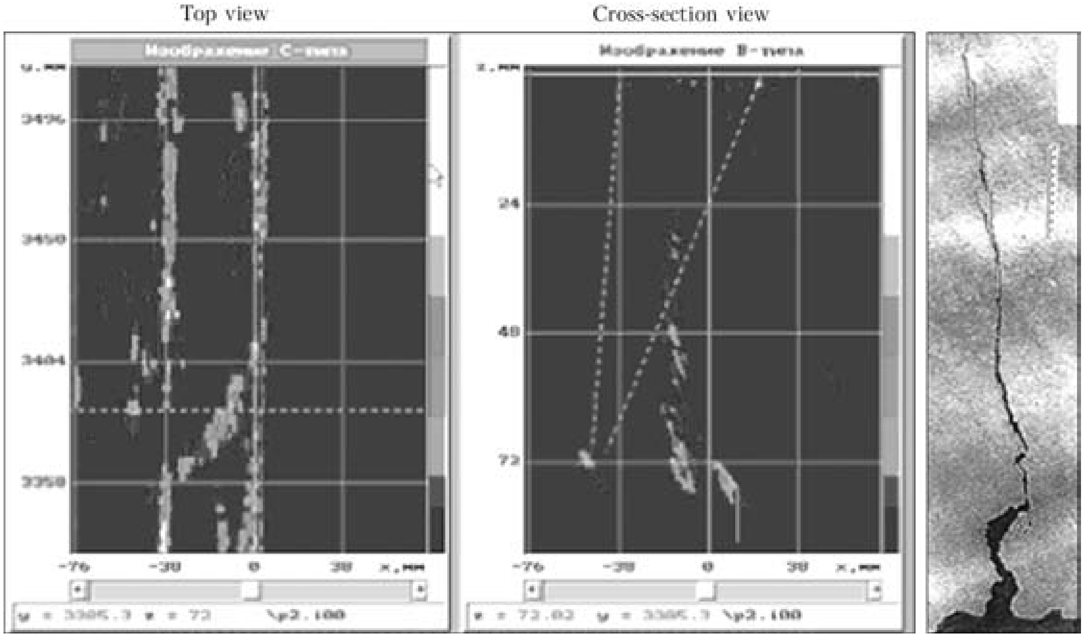


Figure 7. Image of a defect in welded joint with PET angle of incidence 40°

Figure 8. AVGUR system for automated ultrasonic testing of bends of pipelines of WWR-1000 reactor primary coolant circuit

5 m/s accuracy that is not always met customer requirements.

ETC «Welding and Testing» at the N.E. Bauman MSTU developed a portable device ASBAT (Figure 9, *a*) for examination of values of mechanical stresses in uniaxial and biaxial stress-strain state in object thickness by measurement of velocities of all three types of waves, namely two transverse waves with mutually perpendicular polarization and one longitudinal. Direction of these waves' propagation is normal to plane of stress action (Figure 10).

The method is based on birefringent effect, i.e. phenomenon of decomposition of acoustic wave into two constituents in anisotropic media,

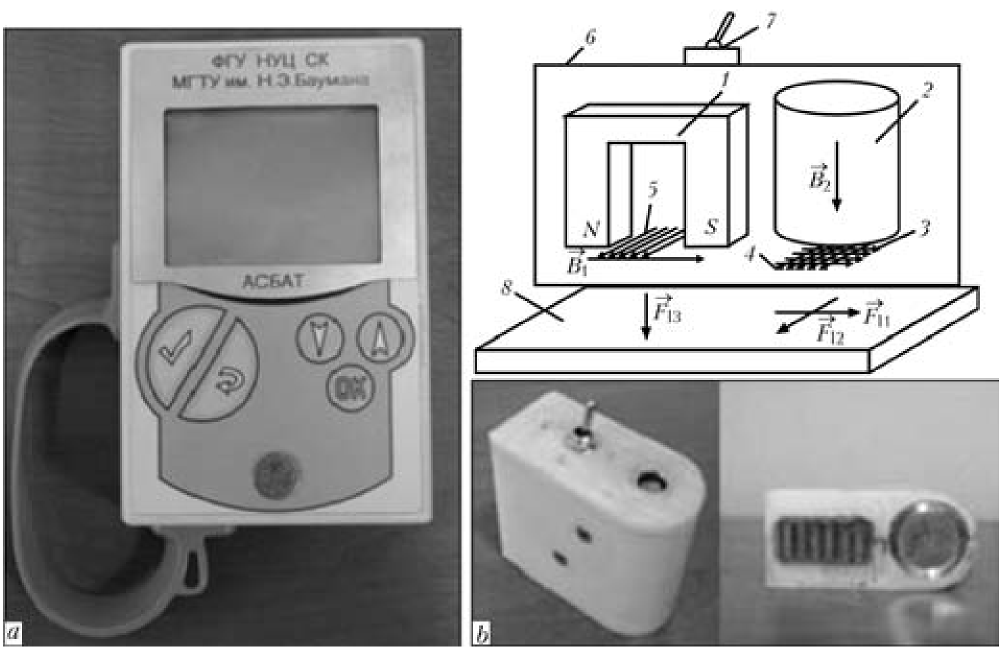
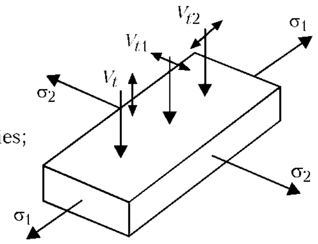


Figure 9. Hardware for contact-free acoustic tensometry (ASBAT) (*a*) and complex sensor (*b*) (*1–7* — see in the text)

$$\begin{cases} V_1 = V_{01}(1 + k_1\sigma_1 + k_2\sigma_2), \\ V_2 = V_{02}(1 + k_3\sigma_1 + k_4\sigma_2), \\ V_3 = V_{03}(1 + k_5\sigma_1 + k_6\sigma_2), \end{cases}$$

where σ_1, σ_1, V_2, V_2 are the stresses and corresponding to them wave velocities; k_1, k_2, k_3, k_4, k_5, k_6 are the coefficients of elastic-acoustic coupling.



For uniaxial stressed state:

$$\sigma_u = K_s(A_s - A_{s0}),$$

where

$$A_s = \frac{t_2}{t_1} - 1 \quad A_{s0} = \frac{t_2^0}{t_1^0} - 1;$$

For biaxial stressed state:

$$\sigma_{u1} = K_1\Delta_1 - K_2\Delta_2, \qquad \Delta_1 = \left(\frac{t_{01}}{t_{03}}\frac{t_3}{t_1} - 1\right),$$

where

$$\sigma_{u2} = K_3\Delta_2 - K_4\Delta_1, \qquad \Delta_2 = \left(\frac{t_{02}}{t_{03}}\frac{t_3}{t_2} - 1\right),$$

where A is a value of acoustic anisotropy; t_1, t_2 are the delays of transverse wave pulses V_{t1} and V_{t2}, respectively.

Figure 10. Procedure for determination of integral by thickness value of mechanical stresses

where particle oscillations in these two waves are mutually perpendicular (Figure 10). Complex EMA-transducer (Figure 9, *b*) was developed for realization of this effect.

Two magnetic systems *2* and *1* are located in single body *6*. Magnetic system *2* (with alternating current coil *3*) is designed for excitation of transverse wave in testing object *8* under effect of Lorentz force F_{12}. Magnetic system *2* (with alternating current coil *4*) is designed for excitation of transverse wave in testing object *8* under effect of Lorentz force F_{11}. Coils *3* and *4* are located one under another and have mutually perpendicular orientation for excitation of the transverse waves with mutual perpendicular polarization. Magnetic system *1* (with alternating current coil *5*) is designed for excitation of a longitudinal wave in testing object *8* under effect of Lorentz force F_{13}, which is directed normal to the testing object. Switch *7* is intended for mode selection.

Realization of multiple echo-signals of shear waves with radial polarization in the anisotropic plates and shear waves with linear polarization at 45° displacement in rolling direction is typical by division of pulses which is clearly observed already for second-third echo-signal depending on level of material anisotropy. This can be explained by the fact that the shear waves in process of their propagation are splitted into two waves with oscillatory displacements along and across the rolling direction, propagating with different velocities.

Increase of the material anisotropy rises the mutual time displacement of pulses of both components of the shear waves at constant path of

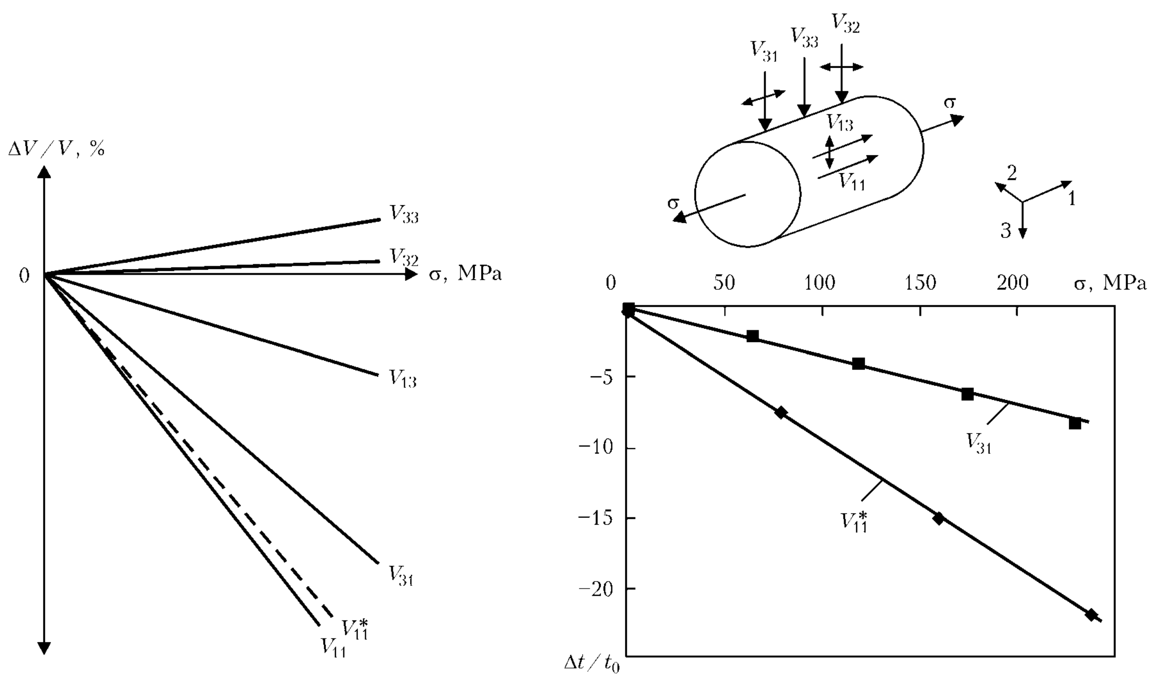


Figure 11. Dependence of head wave sensitivity on mechanical stress: V_{11} — longitudinal; V_{11}^* — head; V_{13} — Rayleigh; V_{31}–V_{33} — transverse waves

their propagation in the material (constant thickness). Relative time of displacement of wave pulses with different polarization achieves the value of interval of double propagation of each wave in layer thickness and exceeds it at sufficiently large path of signal propagation.

Level of anisotropy rises at application of load to testing object along one of the anisotropy axes, thus the mutual time displacement of pulses of two waves with mutually perpendicular polarization increases. Change of relative difference of wave velocities in initial (unloaded) and final (loaded) state is proportional to effective stress.

The authors proposed applying a head wave in contact variant for providing higher sensitivity to the mechanical stresses. Experiments and calculations showed that it sensitivity is 2.7 time higher (Figure 11) in comparison with transverse wave for steel 30.

ASBAT passed interdepartmental tests and after corresponding certification was implemented at OJSC «Gazprom» objects.

Received 12.04.2013

FUNDAMENTALS OF TECHNOLOGY OF ELECTRIC CONTACT SINTERING OF NANOSTRUCTURED METAL-POLYMERIC COATINGS OF TRIBOTECHNICAL PURPOSE

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Model-theoretical approaches to optimization of structure-technological conditions of electrocontact sintering of metal-polymer coatings are presented. It is shown that application of methods for computer simulation of zones of powder composite materials formation based on principles of mesomechanical approach using structural models, adapted to wide range of technological parameter values and properties of powder system initial components, allows determining the dependencies of effect of technological factors and structural peculiarities as well as characteristics of initial components of dispersed powder systems on processes of sintered layer structure formation. At that, consideration of local effect of thermal factors and internal stresses, appearing in process of coating formation, has the defining importance. 4 Ref., 1 Table, 9 Figures.

Keywords: *electrocontact sintering, metal-polymer composite coatings, copper matrix, computer simulation, sintering parameters, structure-technological factors, coating formation*

Application of the composite self-lubricating materials, nanostrucutred by carbon nanotubes and nano-onions, and coatings, based on powder cooper matrix [1], in friction assemblies, is a perspective direction for increase of service life and expansion of loading-speed ranges of machine and mechanism operation. However, introduction of polymer fillers and carbon nanostructures directly in powder charge, using known technological methods, and obtaining of quality metallic matrix-based materials by traditional methods of the powder metallurgy is significantly complicated due to low melting temperatures and heat resistance of polymers. This problem can be solved by electrocontact sintering method [2, 3] relating to series of high-speed and high-energy methods for production of materials and coatings from powder composites. Thus, its main peculiarity lies in the possibility of obtaining of coatings from powder materials with different physico-chemical properties.

It should be noted that properties of the composite materials with metallic matrix are caused by effect of a number of factors, i.e. properties, quantity and type of matrix and filler; type and nature of filler distribution in the matrix; composite structure and technology of its production; external impacts. Therefore, information about mechanisms, stipulating presence in the composite of that or another properties, possibility of prediction and regulation of nature of heat-transfer and structuring process development in the course of contact interaction of dispersed components of the metal-polymer systems, in particular, at high-speed heat impact by electric current, will allow rational application of existing composite materials and creation of new ones with high level of service characteristics [4].

Serious problems appear in process of formation of structure and properties of nanofilled metal-polymer powder coatings. They are related with the fact that powder metallic matrices and dispersed inclusions receive different types of thermal stresses depending on level of temperature effect and heat evolution type, determined by technological and structural factors, at high-speed impact by electric current. It is reasonable to consider such powder systems as a structural sequence, including dispersion matrix, contact interaction zone and dispersed filler. Therefore, investigation of thermal-stressed state of nanostructured metal-polymer dispersed systems at high-speed impact by electric current and determination of dependencies of structural transformations in zones of metal-polymer contact interaction is sufficiently complex and unconventional task from point of view of thermomechanics of adaptive materials.

Model-theoretical approaches to optimization of parameters of powder coating electrocontact sintering. One of the important technological parameters of powder composite electrocontact sintering is a sintering time which to significant extent influences the nature of processes of structure formation in powder layers and determines the strength characteristics and quality factors of the materials. The time of electrocontact sintering of metallic powders and composite coatings on their basis has also significant influence on the nature of accompanying electrophysical processes in powder layer. In particular, it affects the level of influence of pinch effect, which can result in distortion of surface form of powder layer, as well as skin-effect, generated by electric current and appearing in metal. The latter lies in a displacement of line of electric current passage to the surface of current conducting element and can result in preferred powder sintering on a periphery of powder layer. At that, appearance of impact waves and their dissipation is possible during release of energy at electric current passage through the powder system. In this connection optimization and determination of efficient time for sintering of powder compositions are sufficiently important in development of technology for formation of composite powder coatings by electrocontact sintering. Such a time provides for achievement of temperatures of powder system sintering and set strength characteristics of the metallic matrix.

The model-theoretical investigation of appearing physical processes was carried out in order to determine the optimum time for sintering of powder thin-layer coatings, taking into account nature of effect of some factors indicated above. Procedure for simulation of stages of electric current passage through mesofragment of bulk powder copper layer and computer structural models of zone of contact interaction electrodes — powder layer were developed for that. They describe thermal and stress-strain state of the materials during external impact as well as allow observing the development of electrodynamic and thermal processes in the mesofragments of powder layer, formed by electrocontact sintering, in real time.

The investigations were carried out for the case of coating formation with 300 μm thickness of bulk layer from copper powder of PMS-1 grade of 100 μm particle size on a surface of copper substrate using electrodes, manufactured from M1 grade copper, when electric current density makes 400 A/mm^2. The algorithm for solving of specified problem is the following, namely detailed description of model with statement of investigation object and specification of bonds of system components; model formalizing; model programming with statement of selected means; testing of the model and receiving of reliable results. The table shows the physical characteristics of materials necessary for simulation. Temperature resistant coefficient for copper corresponded to 0.0068 deg^{-1} value and heat-transfer coefficient made 5.2 W/m^2 deg at 0.2 m/s of velocity air flow for closed spaces.

In general case, if the electric current is passed through the powder layer, the whole process can be divided on a number of stages and consider sintering of powder material on each stage as a separate process, the initial parameters of which are the final calculated parameters of a previous stage.

The first stage of up to 0.3 s duration has significant importance in electrocontact sintering. Rapid current increment takes place when applying difference of potentials to sintered powder layer. The time during which current increment takes place has no dependence on form and cross-section area of pressing, but at the same time depends on its height, namely rise of the height promotes increase of the increment time. However, it should be noted that the time of current increment significantly reduces with the increase of applied force and supplied stress.

The typical peculiarity of the first stage is preferred heat evolution on interparticle contacts, caused by current passage through the surface low-conductivity layers (Figure 1, *a*).

Properties of calculated model elements for mesofragment of electrocontact sintering zone of powder layer

Model element	Material	Thermal conductivity coefficient λ, W/(K·m)	Specific heat capacity *C*, J/(kg·K)	Specific electric resistance ρ, Ohm·m	Density γ, kg/m^3
Electrode	Copper M1	390	$0.38\cdot10^3$	$1.68\cdot10^{-8}$	$8.93\cdot10^3$
Powder	Copper PMS-1	365	$0.39\cdot10^3$	$1.6\cdot10^{-8}$	$7.2\cdot10^3$
Oxide layer	Cu_2O	1.013	$0.429\cdot10^3$	$2.14\cdot10^{-4}$	$6\cdot10^3$
Pores	Air	0.027	$1.009\cdot10^3$	–	1.293

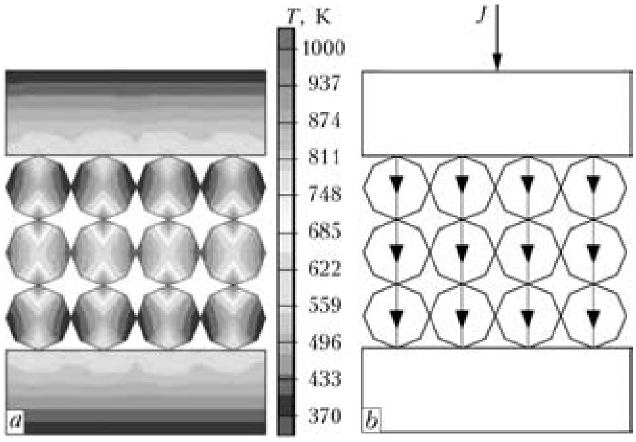

Figure 1. Results of simulation (*a*) and scheme of electric current passage (*b*) on the first stage of process of powder copper layer electrocontact sintering at sintering time 0.3

At the some time possible formation of sparking should be noted. The electric current on the first stage flows parallel to electric field intensity lines forming at that separate chains (Figure 1, *b*). At that, current in each chain has approximately similar value. Thus, it should be noted that there is no heating of the particles at the beginning of sintering process and preferred heat evolution takes place at contact resistance. The average temperature of powder layer on the first stage does not exceed 573–623 K. In the case, when intensity of heat evolution at current passage through the powder layer exceeds the heat input spent for metal heating in zone of contact interaction of particles in solid phase up to melting temperature, as well as for convective heat exchange with ambient environment and heat transfer in the electrodes, then part of metal can liquate.

On the second stage, the temperature of contact surfaces of powder material particles significantly exceeds the temperature of particles and it is enough for melting of oxide film and part of the metal due to heating taking place durin electric current passage according to Joule–Lentz's law. Quick evolution of large quantity of heat energy in vicinity of the interparticle contact can result in chipping of the smallest particles being in solid phase. However, this phenomenon has not significant effect on sintering process. Repulsive forces, appearing as result of heat expansion, reduce more than 10 times in melting of oxide layer and insignificant part of metal being in contact interaction. The liquid-metal bridges are formed as a result of part of metal melting. It should be noted that the specific electric resistance of liquid copper exceeds the specific electric resistance of solid copper in several times. In particular, heating of copper to 970 °C promotes rise of specific electric resistance up to $9.6\cdot10^{-8}$ Ohm·m. Loss of stability and destruction of the liquid-metal bridges take place during temperature increase, reduction of pressure and, as a consequence, increase of electric resistance in particle contact. This inevitably leads to change of path of electric current over powder layer, and current passes through unmelted contacts which have lower resistance. Thus, similar liquid-metal bridges appear on other contacts of the powder particles.

Duration of the second stage starts on 0.3 s and finishes on 0.6 s. At that, results of computer simulation showed that the average temperature in powder layer on this stage exceeds 623 K. Since, the second stage of electrocontact sintering of powder material is characterized by large number of changes in electric current paths, it should be divided on several stages during simulation.

The paths of electric current lines and model of thermal state of mesofragment of zone of powder layer electrocontact sintering on the first step of the second sintering stage are shown in Figure 2, Figure 3 shows the second step of the

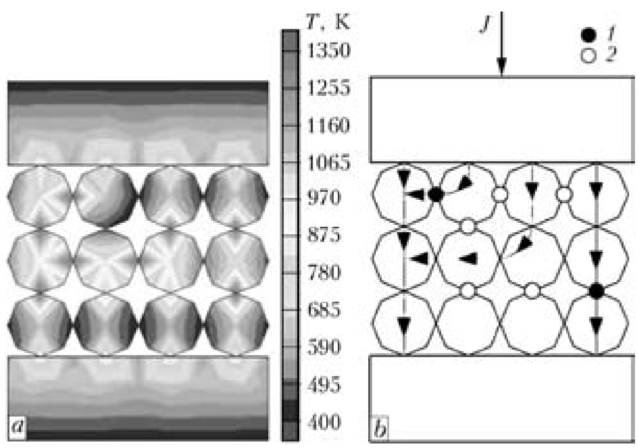

Figure 2. Results of simulation (*a*) and scheme of electric current passage (*b*) on the first stage of the second step of process of powder copper layer electrocontact sintering at sintering time 0.4 s: *1*, *2* — contacts in which metal is in solid-liquid and liquid state, respectively

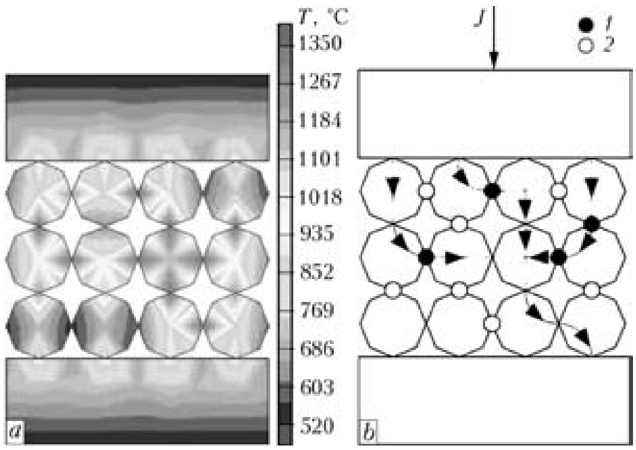

Figure 3. Results of simulation (*a*) and scheme of electric current passage (*b*) on the second stage of the second step of process of powder copper layer electrocontact sintering at sintering time 0.5 s (marks *1*, *2* are the same as in Figure 2)

second stage and Figure 4 represents the third step of the second sintering stage.

It can be seen in the represented models that the electric current paths cover all the contacts at increase of sintering time, melt them, thus promoting joining of cooper particles and sintering of powder system. At that, the results of computer simulation of thermal state of copper powder layer in the process of electrocontact sintering showed satisfactory correlation with the results of experimental investigations. As current has passed through the interparticle contacts, their melting is accompanied by increase of electric resistance and described above process repeats again up to melting of all metal particles or stop of current supply. The metal in particle contact areas transforms in molten or much softened state. The particles of powder system begin insignificant displacement relatively to each other that result in compacting of composite material.

Insignificant quantity of liquid phase is formed and intensive sintering of powder system

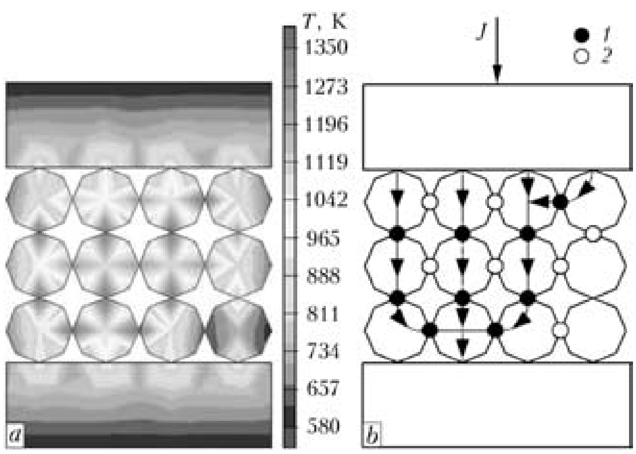

Figure 4. Results of simulation (*a*) and scheme of electric current passage (*b*) on the third stage of the second step of process of powder copper layer electrocontact sintering at sintering time 0.6 s (marks *1*, *2* are the same as in Figure 2)

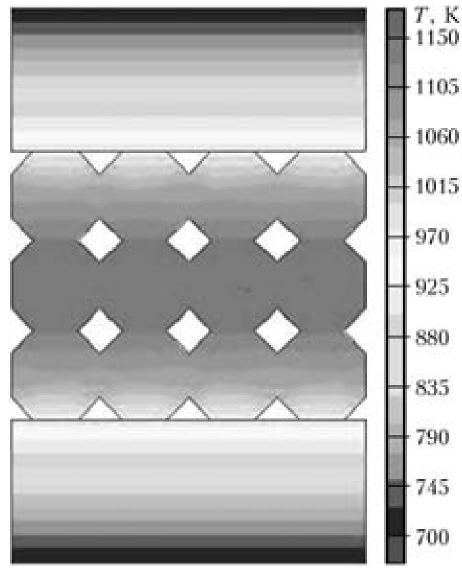

Figure 5. Model of combined thermal and strained state, formed by powder copper layer electrocontact sintering on the expiry of sintering time, making 1.2 s, under effect of 150 N compressive load on mesofragment

takes place as the result of processes described above. Increase of powder system average temperature, which achieves 1073–1123 K values and corresponds to temperatures of copper matrix sintering, should be noted on the final third stage which starts on 0.6 s and finishes in 1.1–1.3 s time range. Finishing of the processes of powder layer compacting by means of plastic deformation (Figure 5) also takes place on this stage. Increase of powder system pressure by force application to the electrode promotes rise of the stress in particles and their elastic deformation. After stresses in the particles exceed the material yield strength, their plastic deformation takes place. Material of the particles tends to fill initial interparticle pore space. Density of the material increases as a result. At that same time, reduction of contact resistance between the particles takes place with increase of contact surface. Herewith, reduction of equivalent stresses by Mises, the maximum values of which make around 112–156 MPa, occurs. The cooper metallic matrix,

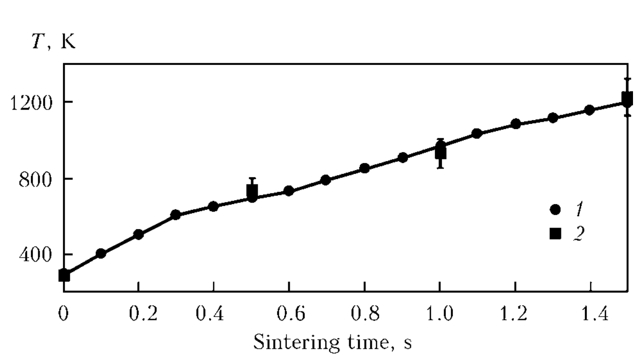

Figure 6. Dependencies of temperature in powder layer on sintering time under electric current impact: *1* — results of computer simulation; *2* — experimental value

having relative density 80–90 %, is formed as a result of electric current impact and pressure application. It should be noted that resistance of pressing increases with reduction of geometry of sintered powder system particles. This phenomenon can be explained by the fact that increase of quantity of specific volume components of the system promotes directly proportional rise of quantity of electric contacts due to what powder layer conductivity is reduced.

Figure 6 shows the temperature dependencies of powder layer, obtained as the result of computer simulation of thermal state of zone of copper powder layer electrocontact sintering using developed structural model. The latter considers structural peculiarities of the formed powder composite as well as results of experimental investigations. Determination of temperature in the powder layer was carried out on specially designed operating prototype of the unit at its joined application with seam resistance welding machine MSh-3207 in mode of spot sintering. Copper powder layer was loaded only by effect of electrode force. Registration of temperature in sintering zone was performed with the help of chromel-alumel thermocouple by electronic potentiometer Memograf with automatic signal processing. It is equipped with RS485 interface for feature determination and data transfer in the computer.

As can be seen, the difference between temperature values, received as a result of experimental investigations and computer simulation, does not exceed 10–15 % in the whole range of changing of sintering time that can be considered sufficiently acceptable in the case of formation of powder layers using given high-speed electrocontact sintering method.

Model-theoretical description of structural-technological factor effect on thermal state of zone of formation of metal-polymer powder copper-based coatings in process of electrocontact sintering. The issues of theoretical description and investigations of processes of transfer and distribution of heat in coating formation zones gain a particular importance in electrocontact sintering of powder metal-polymer systems. At the same time, it should be considered that quick evolution of heat energy in vicinity of the interparticle contact due to electric current passage, and, in particular, when dielectric spaces (air, dielectric filler, oxide film, etc.) are present between the adjacent metallic particles, can result in appearance of different phenomena, determined by electric, thermalphysical and mechanical characteristics of the components. Investigation of thermal state of the electrode-dies also provokes a scientific interest, since dimensions of area of contact with sintered material and nature of powder composite system have significant influence on processes of heat distribution in them. It should also be noted that theoretical description, examination and analysis of temperature distribution fields, temperature gradient and heat flows as well as obtaining of proper investigation results allow optimizing and predicting temperature distribution, heat flows and temperature gradient inside the composite met-

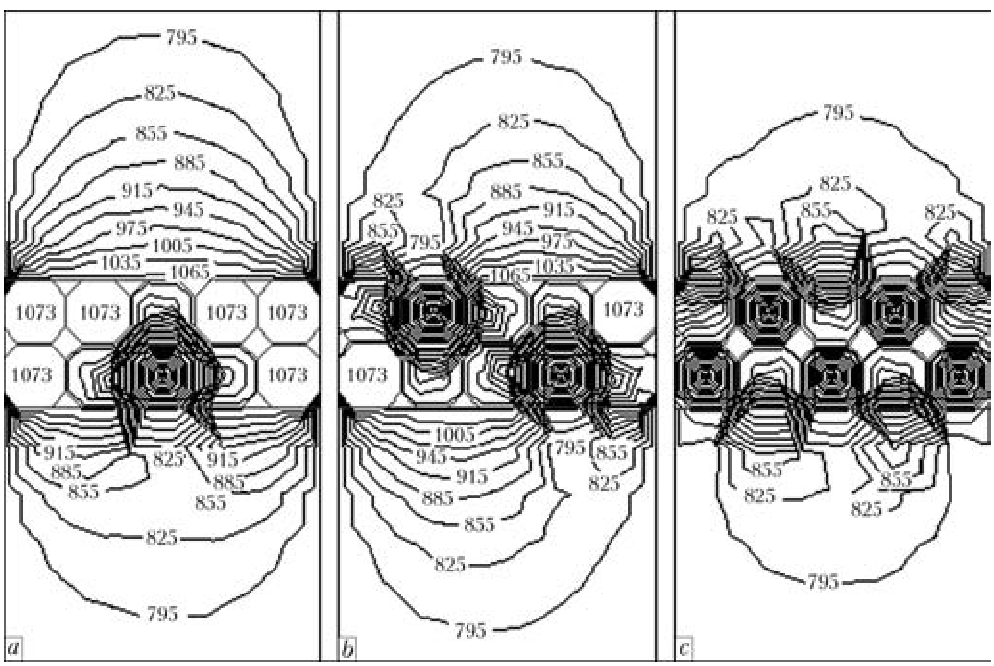

Figure 7. Models of temperature field distribution in mesofragments of zones of metal-polymer powder layer electrocontact sintering with different level of filling of copper matrix by PTFE particles: *a* — 10 vol.%; *b* — 20; *c* — 50

al-polymer powder material at change of structure-technological conditions.

In view of mentioned above, a computer plane-parallel problem of stationary heat transfer was solved for electrocontact sintering of metal-polymer powder systems with copper matrix, when the temperature between two electrodes and in the sintering zone achieves 1073 K, i.e. sintering temperature of copper powder.

Lets' consider the distribution of temperature fields in zone of formation of powder layer for sintering scheme, when two electrodes are in contact with the whole sintered surface of material — copper powder composite and 10, 20 and 50 vol.% of PTFE, equally distributed in the metallic matrix (Figure 7).

Simulation results showed that the largest electrode heating is observed in sintering of composite with PTFE 10 vol.% (Figure 7, *a*) and it is smaller in sintering of composite containing 20 (Figure 7, *b*) and 50 vol.% (Figure 7, *c*). It is also seen that copper particles, having no contact with polymer, are completely heated to 1073 K temperature, i.e. to sintering technological temperature. Surface area of upper electrode which has no contact with PTFE particles, will also be more heated than lower electrode, where break of isotherms is observed. At that, the level of temperature fields in lower electrode in the zone of contact with polymer PTFE particle is 10–15 % smaller, than in the zone of electrode contact with copper particles. The break of isotherms in the electrodes is observed as well in presence of 20 vol.% of PTFE polymer particles (Figure 7, *b*) in sintering zone. Copper particles, contacting with polymer particles, also have lower temperature in comparison with the particles making not contact with PTFE particles. It can be seen that the temperature loading in central part of zone of metal-polymer material sintering reduces with increase of content of the polymer filler in metallic powder matrix at simultaneous displacement of the regions of electrode temperature equilibrium to periphery areas.

If equal quantity of copper and polymer particles are present in the sintering zone (Figure 7, *c*), than certain temperature stabilization in powder metal-polymer composite layer, significant reduction of heating of both electrodes, increase of quantity of zones of isotherm breaking, but insignificant heating of copper particles for quality sintering of metallic matrix are observed.

Mechanisms of evolution and distribution of heat in volume of the metal-polymer powder system and, in particular, on the boundaries of dispersed metal-dispersed polymer have significant effect on processes of composite powder coating structure formation. It is extremely difficult to evaluate the nature of heat flow distribution in volume of the powder metal-polymer systems as well as distribution of temperature fields and temperature gradients on dispersed metal-dispersed polymer interface by experimental methods due to short-term of the electrocontact sintering process. At the same time, investigation and determination of dependencies of heat transfer processes in such powder systems is sufficiently important on stage of their development.

The structure simulation approaches applying finite-element digitization were used for evaluation of properties of powder composite materials of this class, in particular, in zones of their contact interaction polymer-metal, which are more susceptible to temperature difference between the current-conducting copper particles and non-conductive particles of the polymer. Figure 8 shows the models for temperature field distribution in area of investigation of mesofragment of metal-polymer powder system formation zone at different time of electric current impact in the process of electrocontact sintering. It should be underlined that the peculiarity of given problem is consideration of time of staying of composite powder system in the sintering zone, i.e. non-stationary heat transfer problem is solved. It is assumed in accordance to earlier obtained data that the time of electric current impact on metal-polymer powder system in zone of electrocontact sintering makes from 0.3 to 1.2 s. Current intensity, supplied to heat evolution source, is 12 kA.

The detailed analysis of obtained results allowed determining the following. In consideration of the heating case, when the time of sintering is 0.3 s, the temperature in contact zones between metallic particles of metal-polymer powder system achieves 623 K (Figure 8, *a*) and it makes from 601 to 623 K on the rest of surface of copper particles in the investigated mesofragment.

Smoothing of isotherms takes place at removal from the surface of copper particles to their center. Concentration and localizing of large quantity of isolines is observed in areas of copper particle contact that confirms the observable typical reduction of temperature in given area to 530 K at 25 μm distance from the surface of copper particle to its center. It can be seen in area of contact interaction copper particle — PTFE particle that removal from contact surface to the center of polymer particle promotes temperature reduction from 440 to 390 K, whereas temperature in copper particle increases from 440

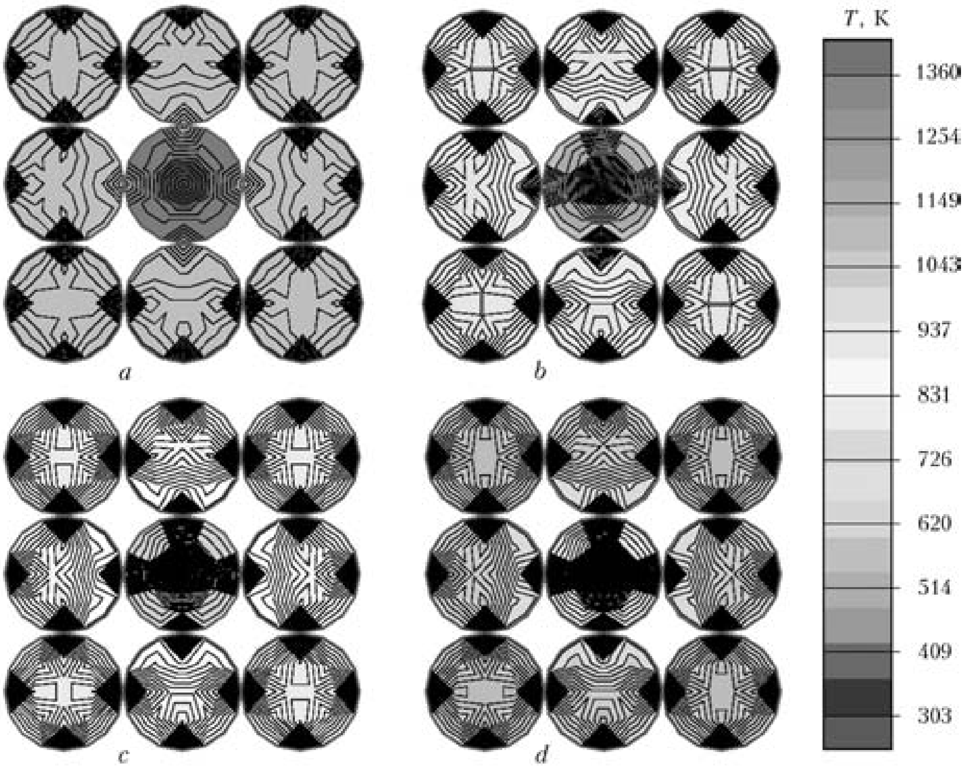

Figure 8. Models of temperature field distribution in zone of contact interaction copper-PTFE at different sintering time: *a* — 0.3 s; *b* — 0.6; *c* — 0.9; *d* — 1.2

to 495 K at consideration of zone of removal from the contact point per 25 μm. At that, the presence of pores in examined mesofragment has significant effect on the level of heat condition in periphery areas.

Increase of level of ohmic heating of metal-polymer powder system is observed at rise of sintering time up to 0.6 s. At that, temperature in zones of contact interaction copper–copper makes around 923 K (Figure 8, *b*) and from 770 to 912 K on the rest of copper particle surface. Change of temperature condition in the copper particles having no contact with PTFE particle occurs in the direction from their surface to the center in such way that temperature at 25 μm distance from its surface makes around 695 K. Reduction of temperature from 584 to 495 K in the direction from the contact surface to the center of polymer particle is observed in area of contact interaction copper particle-polymer particle. At the same time, an opposite picture, characterizing by temperature increase from 589 up to 695 K in consideration of zone of removal from the contact point per 25 μm, is marked in the copper particle.

The temperature in zones of metal-metal contact interaction makes 1223 K (Figure 8, *c*) and from 736 to 1111 K on the surface of copper particles, if metal-polymer powder system is heated during 0.9 s. The temperature reduces at removal from the surface to the center of copper particles, having no contact with polymer particle, and achieves 934 K value at 25 μm radial distance. It can be seen in area of contact interaction copper particle-polymer particle that the temperature decreases to 553 K at removal from the contact surface to the polymer particle center, whereas it rises to 896 K in the copper particle at consideration of zone of removal from the contact point per 25 μm.

When temperature of ohmic heating of powder system achieves 1356 K, that is provided by 1.2 s sintering time (Figure 8, *d*), the copper particles are almost uniformly heated over the whole area up to sintering temperature, corresponding to 1073 K, and areas of local heating up to melting temperature are observed in the points of contact interaction of copper dispersed particles. It is also determined that exceeding of thermal-oxidative degradation temperature of the polymer is observed in local areas of their contact interaction with copper particles at radial distance not exceeding 18–20 μm from the surface of PTFE particle to their center.

The dependencies characterizing effect of time of electrocontact sintering on changing of temperature in typical points of mesofragment of powder metal-polymer system (Figure 9) were built based on obtained results of the model-theoretical investigations.

It should be noted in the conclusion that the proposed model-theoretical approach allows de-

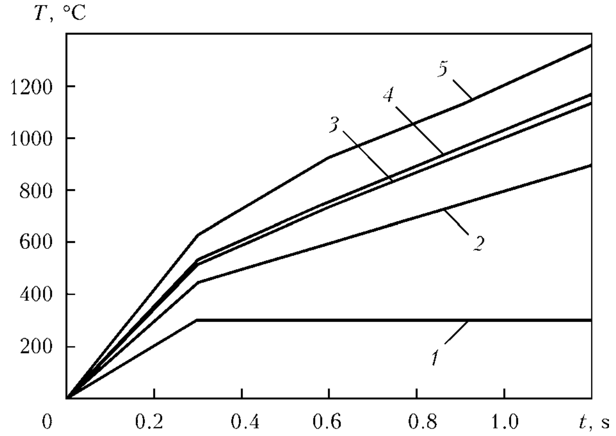

Figure 9. Dependencies of effect of time of metal-polymer powder system electrocontact sintering on temperature change in typical points of composition: *1* — center of PTFE particle; *2* — contact point copper-PTFE; *3*, *4* — center of copper particle, contacting and not contacting with PTFE particle, respectively; *5* — contact point copper–copper

veloping the computer structural models of zones of contact interaction electrodes-powder layer. They describe thermal and stress-strain state of the materials at application of external impact (density of electric current and compression force of the electrodes) under conditions of non-stationary heat transfer. These conditions differ from existing ones by possibility of consideration of effect of electrocontact sintering time, contact interaction of the surfaces and peculiarities of particle structure in powder layer (presence of oxide layer and pore space) on formation of temperature fields, component deformation, temperature distribution and thermal and mechanical stresses. The time of powder system staying in sintering zone at electrocontact sintering, making 1.1–1.3 s, was optimized based on such an approach and complex of carried out investigations at consideration of experimental correlation for specified technological conditions of formation of nanostructured metal-polymer powder coatings with bulk layer thickness 300–500 μm. It provides for the achievement of 1073–1123 K sintering temperature of metallic copper matrix, completion of processes of bulk powder layer compacting by plastic deformation and reduction of equivalent stresses by Mises to 112–156 MPa thickness values in the formed powder coating of 90–100 μm at simultaneous effect of specified loading.

It is shown for the first time that the temperature in diametric section of the copper particles reduces 1.4–1.5 times, at the same time as the temperature in diametric section of the polymer particle decreases 2.8–3.0 times during formation of coatings by electrocontact sintering, when the temperature achieves the values providing extreme conditions of thermal ohmic heating and heat transfer in the powder metal-polymer system. Established effect promotes «relay-race» development of heat transfer processes with appearance of the local thermal stresses in zones of physical contact metal-polymer and concentration of heat energy in surface layer of dispersed polymer particles. Redirection of heat flow distribution takes place due to low values of heat conduction of the polymer filler particles in comparison with the metallic matrix particles as well as high (800–900 °C/s) speed of heating of the composite powder system and short-time of sintering process (around 1.1–1.3 s). This in whole reduces the thermostressed state at dispersed polymer-dispersed metal interface due to what the processes of thermal-oxidative degradation virtually do not develop in the direction to polymer particle center.

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Received 28.02.2013

NON-INVASIVE STRUCTURAL HEALTH MONITORING OF STORAGE TANK FLOORS

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Large above ground storage tanks filled with hydrocarbon and hazardous liquids such as oil, oil-derived products, chemicals and process plant liquids are in widespread use in the UK, Europe and throughout the world. Tank farms are normally located in coastal areas close to large centres of population. Leakage from corroded storage tanks, especially from their floors, is a major environmental and economic hazard and poses a significant threat to those living in the vicinity of tank farms, as well as to the rest of the UK and Europe. The current, and growing, risk of tank failure together with the potential risk for fire and explosion at nearby petrochemical plants is wholly unacceptable. This paper illustrates the work carried out in the UK Technology Strategy Board (TSB) Tank Integrity Monitoring (TIM) project, for the structural health monitoring of large above ground bulk liquid storage tank floors without the need to access the inside of the tank or to empty its contents, using ultrasonic guided waves (UGW) as a non-destructive testing technique. A structural health monitoring system for acquiring ultrasonic guided wave data over long periods of time was developed. The performance of the permanent attached transducers and the structural health monitoring system was also investigated to demonstrate their reliability. The propagation of the guided wave signals has been validated experimentally on a 4 m diameter tank floor, and tomography imaging has been developed for detection and location of defects. 3 Ref., 6 Figures.

Keywords: *guided wave, ultrasonic, tank floor, tomography, storage tanks, structural health monitoring system*

Various NDT methods such as penetrant testing, magnetic particle, radiographic testing, eddy current, thermography and acoustic emission were used to inspect storage tank floors [1, 2]. Current inspection methods require the tank to be drained in order to create a safe environment, suitable for personnel entry, in order to carry out inspections which can be time consuming and expensive. As such, there is a need to develop a faster, lower cost and safer method to assess the structural integrity of tank floors. The objective of this study was to develop a structural health monitoring method for the tank floors using low frequency UGW. The low frequency UGW have the ability to propagate long distances in planar and tubular structures and is already used for the inspection of pipes [3].

Experimental set-up. *Tank monitoring system.* A 4 m diameter tank floor was used to carry out the structural health monitoring experiments for damage locality and detection. The wall thickness of the tank floor was 7 mm with a seam weld running along the diameter of the tank floor. The tank is shown in Figure 1.

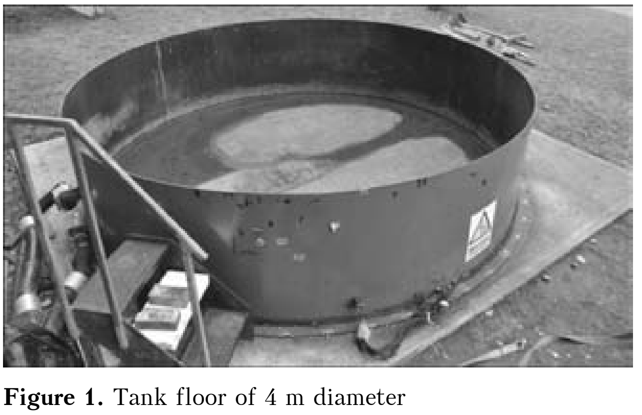

Figure 1. Tank floor of 4 m diameter

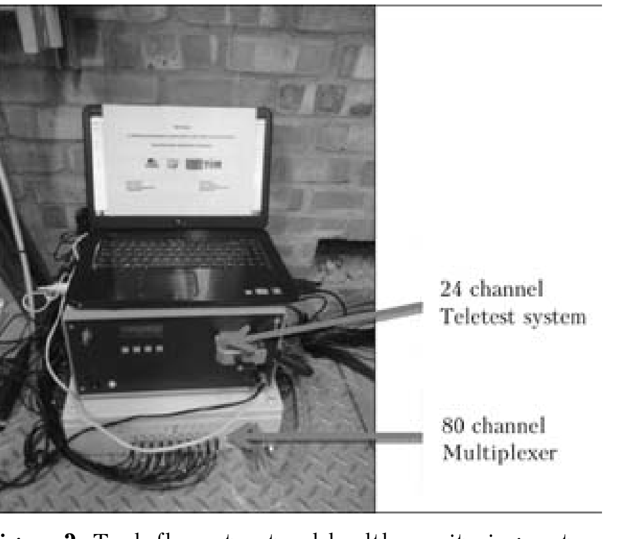

Figure 2. Tank floor structural health monitoring system

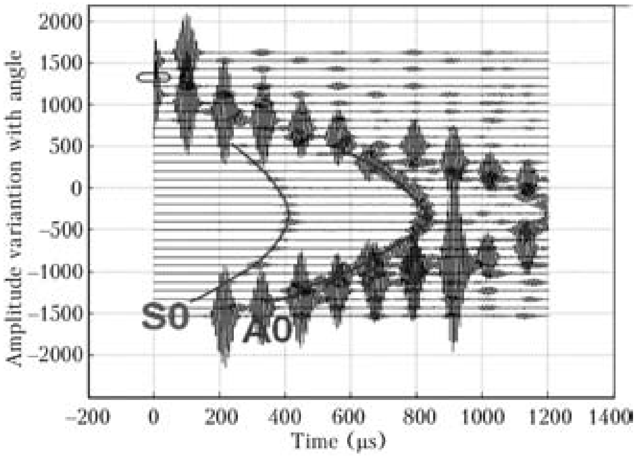

Figure 3. Time domain signals acquired

A multitude of transducers were permanently attached around the perimeter of the tank floor. The commercially available 24 channel Teletest system and an additional 80 channel multiplexer were used to collect a broadband frequency range of data. The botany of the tank floor structural health monitoring system is illustrated in Figure 2.

Ultrasonic guided waves. The ultrasonic guided waves propagating within the plate structure contain various wave modes; depending on the frequency of excitation, the fundamental wave modes generated are the symmetric S0 and asymmetric A0 wave modes. In this study, the characteristics of the S0 wave mode are used. The presence of the S0 and A0 in the acquired time domain signals is illustrated in Figure 3.

Result. *Reliability*. The structural health monitoring system was used to collect data continuously over three months. One very important factor for a robust structural health monitoring system is the reliability of the transducers and electronics. The stability of the aforementioned transducers, which were studied over the three month time period, are illustrated in Figure 4, the results of which can be displayed using tomograms that were intermittently generated. It can be seen that the distribution of the energy over the circular structure is fairly constant over a prolonged period of time suggesting no failure or degradation in the performance of the transducers and electronics.

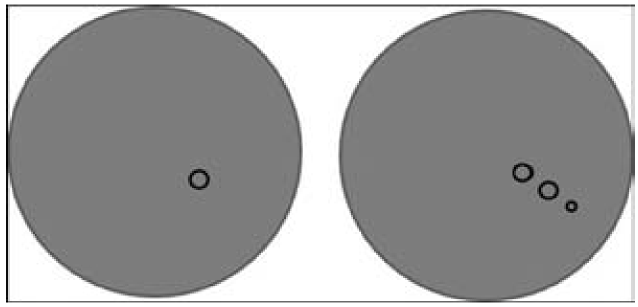

Figure 5. Defect size and location: 70 mm defect (*left*) and 70, 70 and 20 mm defect (*right*)

Defect detection and location. The capability of defect defection in terms of size and location was studied. A large set of baseline data were acquired which covers wide environmental condition changes. A single defect of diameter 70 mm and through thickness were introduced initially, then a second and third defect of 70 and 20 mm, respectively, were then added to the tank floor. A set of data was then collected after each defect addition. The positions of the defects are shown in Figure 5.

The tomograms were generated using characteristics of the S0 wave mode acquired at the

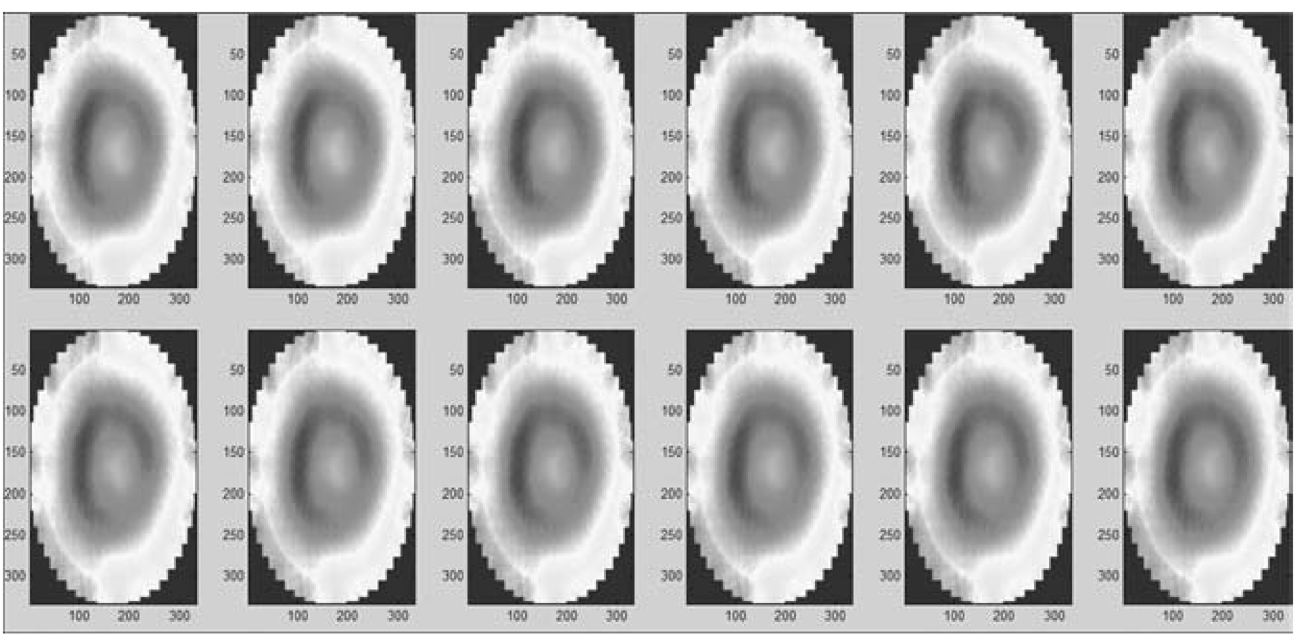

Figure 4. Tomography representation for the stability of transducers

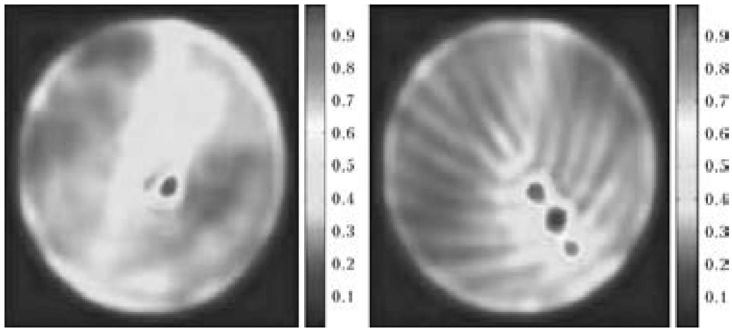

Figure 6. Tomograms for 70 mm defect (*left*) and for 70, 70 and 20 mm defects (*right*)

opposite receiving transducers. The detection and location of the added defects have been made possible by the tomography technique used. The tomograms are shown in Figure 6.

Conclusion

The use of ultrasonic guided waves for the structural health monitoring of storage tanks has been investigated on a 4 m diameter tank floor. For the purpose of structural health monitoring, it is of paramount importance to have a reliable system in terms of transducer performance and a stable pulser-receiver system. The experiments carried out, based on the data acquired, demonstrate the stable performance of the permanently attached transducer and of the pulser-receiver used. The S0 wave mode from the receiving transducers has been used to generate the tomograms. The tomography technique has been successfully implemented alongside the developed structural health monitoring system for the detection and location of defects of 20 to 70 mm in size.

Acknowledgements. *The work was sponsored by the Technology Strategy Board (TSB) under the Tank Integrity Monitoring (TIM; www.tim-project.co.uk) project. The project was managed by TWI Ltd (UK). The author would like to express thanks for the support from the TIM project partners namely Shell, Vopak and NuStar Energy.*

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Received 06.06.2013

NUMERICAL SIMULATION AND EXPERIMENTAL INVESTIGATION OF REMELTING PROCESSES

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The numerical simulation of remelting processes enables us to link the local solidification conditions to the operating parameters. Here, we discuss some recent studies aiming to develop specific aspects, e.g. the alternating current distribution during ESR of steels and superalloys, the ensemble arc motion in a VAR furnace and the influence of electromagnetic stirring on the macrosegregation in remelted ingots. 27 Ref., 1 Table, 5 Figures.

Keywords: *vacuum arc remelting, numerical simulation, electromagnetic stirring, current distribution, macrosegregation*

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 VAR (vacuum arc remelting) process, as illustrated in 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 [1]. 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 order to stabilize the arc, it can be confined with the aid of an axial magnetic field created by an external induction coil. The interaction with the melting current stirs the liquid metal, the rotation induced being in the orthoradial direction. By reversing periodically the coil current, stirring can be alternated.

In the case of electro slag 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 [2]. The energy is both transferred to the electrode for the melting and to the secondary ingot. Molten metal is produced

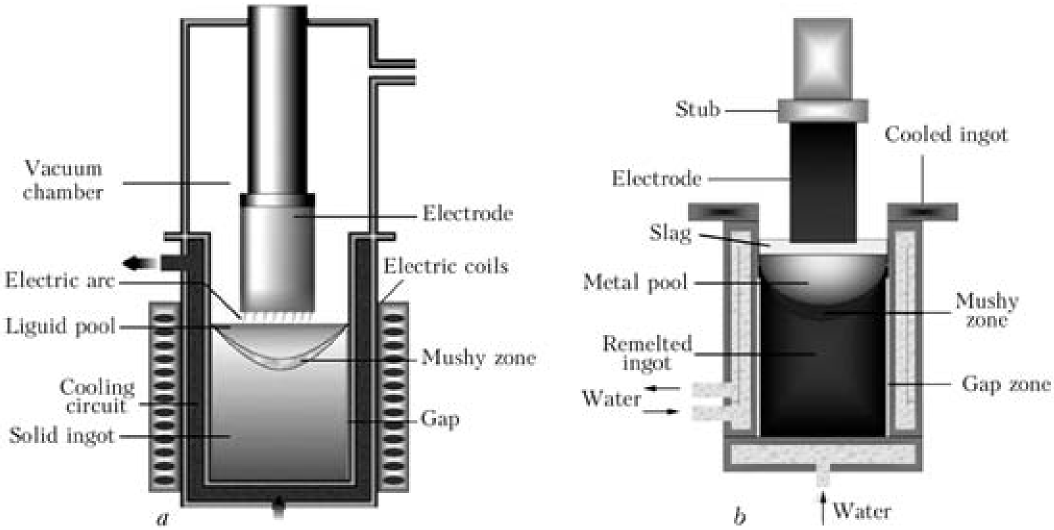

Figure 1. Schematic representation of the VAR process (*a*), the ESR process (*b*)

in the form of droplets which fall and build up the secondary ingot, as shown in Figure 1, *b*. Insulation from air and chemical refining, due to the presence of slag, improve the inclusional quality.

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 understanding, since it allows us 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 some twenty years ago in Institut Jean Lamour to develop numerical software for simulating the remelting operations, and subsequently to help optimizing the processes. The first version of the numerical model SOLAR (which stands for SOLidification during Arc Remelting) was applied to the simulation of VAR for reactive metals [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]. 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 general description of both models (i.e. SOLAR and SOLECS, which stands for SOLartype Esr Complete Simulation) and their validation was part of a communication at the International Conference on Welding and Related Technologies into the Third Millenium, which was held in Kiev in 2008 [7]. Here, we will focus our attention on 3 recent studies aiming to develop some specific aspects of the behavior of actual remelting processes.

Current distribution during electroslag remelting. During the last years, several researches have been presented, aiming to simulate the whole process in a transient way, or discuss in more detail the electromagnetic fields in ESR [8–13]. Among these models, the simulation software SOLECS was developed at IJL, as stated in the Introduction. During the growth of the ESR ingot, the slag is in contact with the water-cooled mould, which is responsible for the formation of a layer of solidified slag at the interface. As the secondary ingot rises, this layer is partially remelted and crushed between the metal and crucible, resulting in a slag skin which acts as a thermal insulator and provides ESR ingots with a smooth lateral surface [2].

In the paper by Weber et al. [6] it was written that «*we assume that the solidified slag skin insulates electrically the slag and ingot from the mold. This assumption is particularly questionable and needs to be confirmed. Indeed, in some cases, the model predicts a discontinuous solid skin surrounding the slag cap, implying a possible electrical contact between liquid slag and mold*». While this strong assumption is made classically in the literature devoted to ESR simulation, [14, 15] it was sometimes claimed [16, 17] that a certain amount of current is able to flow into the Cu crucible. This phenomenon could modify the thermohydrodynamic behaviour of the slag and liquid pool, hence influencing the solidification process. Therefore, the goal of our study is to quantify this phenomenon, and determine the impact of the solid layer thickness and electric conductivity of the solidified slag on the current distribution during electroslag remelting.

To reach the water cooled crucible and baseplate, the melting current supplied to the electrode and liquid slag can either flow in the ingot pool or directly through the solidified slag skin. The resulting current distribution depends on the electrical resistance of that phase, hence the solid slag conductivity and skin thickness. In this section, we present the computation of electromagnetic phenomena with a simplified geometry. The thickness of the solidified slag skin is assumed to be uniform and the assigned electrical conductivities are estimated values. The main input data are gathered in Table.

Parameters used in the simulations

Melting current (maximum value)	10 kA
AC frequency	50 Hz
Electrode radius	26 cm
Mould external radius	30 cm
Mould thickness	2.5 cm
Electrode immersion depth	1 cm
Electrical conductivity of the metal	10^6 $\Omega^{-1}\cdot m^{-1}$
Electrical conductivity of the liquid slag	400 $\Omega^{-1}\cdot m^{-1}$
Electrical conductivity of the solid slag	10^{-3}–400 $\Omega^{-1}\cdot m^{-1}$
Thickness of the solidified slag skin	4 / 6 mm

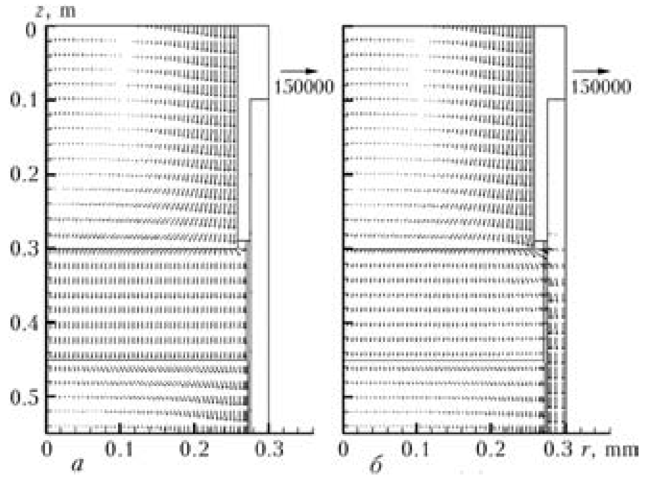

Figure 2. Current density distribution ($A \cdot m^{-2}$) computed with two values for the electrical conductivity of the solidified slag skin: $10^{-3}\ \Omega^{-1} \cdot m^{-1}$ (*left*) and $15\ \Omega^{-1} \cdot m^{-1}$ (*right*)

The effects of the variations of two parameters (electrical conductivity and thickness of the solid slag layer, written with italic characters in Table) on the current distribution and resulting Joule heating were studied. The electrical conductivity was allowed to vary in the range 10^{-3}–400 $\Omega^{-1} \cdot m^{-1}$ ($10^{-3}\ \Omega^{-1} \cdot m^{-1}$ corresponds to a full insulation while 400 $\Omega^{-1} \cdot m^{-1}$ is the conductivity of the liquid slag). The thickness of the solidified slag skin was set to 4 or 6 mm. In the literature, the computed current distribution is most often represented by visualizing the magnitude of the current density phasor (i.e. the maximum value for each component of the current density), which classically leads to the observation of an important skin effect in the electrode and ingot [6, 11, 14, 18]. Indeed, it is well known that the current distribution is related to the value of the skin depth into the different materials: if the latter is larger than the actual dimension of the domain, the current distribution is homogeneous, e.g. into the liquid slag. However, within this study, we chose to represent the instantaneous current distribution at a precise moment in the alternating period $t = 0$. In addition to the visualization of the skin effect, such a representation also highlights the local variation in the phase angle caused by the variation in the induced magnetic field into the metallic conductors, as it was shown by Li et al. [13].

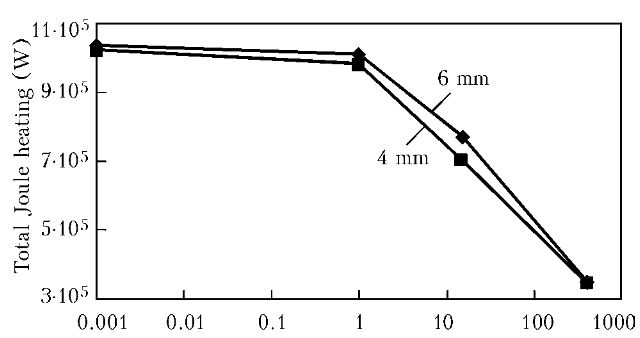

Figure 3. Evolution of the total resistive heating in the slag, according to the electrical conductivity and the thickness of the solidified slag skin

The first step of the study consists in confirming that part of the melting current is likely to flow through the solidified slag layer and directly enter the mould. Figure 2 presents the computed results obtained either when the solid layer behaves as a perfect insulator (such behaviour is reached as soon as the electrical conductivity is lower or equal to $10^{-3}\ \Omega^{-1} \cdot m^{-1}$) or when the electrical conductivity is set to 15 $\Omega^{-1} \cdot m^{-1}$. The solidified slag skin is supposed to be 4 mm thick. Clearly, when the electrical conductivity of the solid slag is set to 15 $\Omega^{-1} \cdot m^{-1}$, part of the current actually flows through the skin to reach the mould. The solidified slag layer does not act as a perfect electrical insulator and this modifies the current distribution in the system. Our result confirms some previous claims in the literature [16, 17] and raises new questions regarding the consequences of such a loss of current on the process efficiency.

Figure 3 summarizes the effects of a variation in the electrical conductivity of the solid slag and in the thickness of the solidified slag layer: it represents the evolution of the total Joule heat generated according to both parameters. The electrical conductivity of the solid slag appears to be a crucial parameter of the process. This observation emphasizes the necessity to have access to actual measurements. The thickness of the solidified slag layer also influences the current distribution in the system. However, in the range of tested values, the impact of this factor remains of secondary importance.

In its present state, this model considered a uniform layer thickness along the slag/crucible interface. However, this parameter is liable to vary from a negligible value to few millimetres during a real remelting. To take into account this variation, as well as to assess the influence of the electrical current distribution on the ingot solidification, the next step of our study will consist in a full coupling of the model with a numerical simulation of the whole ESR process. Results obtained will be compared to actual experimental observation.

Ensemble arc motion during vacuum arc remelting. Knowledge of the electric arc behaviour in the VAR process is based on visualization studies performed first at Sandia National Laboratories [19] during the remelting of steel or Ni-based superalloy electrodes. Similar experiments have then been carried out by Chapelle et al. on Zr electrodes [20]. A conclusion from these observations is that the behaviour of the arc is similar to the diffuse mode of a vacuum arc created between cold solid electrodes. The arc consists of several dispersed clusters of cathode spots moving over the whole surface of the cathode. Such behaviour seems to imply that the total energy transferred from the arc to the cathode tip is distributed uniformly; in particular, no azimuthal direction is privileged, so an axisymmetric behaviour is expected at the macroscopic scale, consistent with the flatness of the cathode tip during full-scale melting.

However, it has been recently reported that the arc often does not behave axisymmetrically at the macroscopic scale. Based on measurements of the luminosity and magnetic field created by the arc [21, 22]. Ward et al. suggested that most of the time, the electrical centre of the arc was rotating in a time-averaged sense around the ingot centreline with a constant speed (period equals typically 20 to 40 s when a superalloy electrode melts under nominally diffuse conditions). Then it was assumed that the distribution of current flow and heat input followed the distribution of this location and a part of the arc was assimilated to a loosely focused rotating spot, radially located away from the ingot centreline. A 3D model of the ingot pool, using this representation as a boundary condition, [23] enabled the authors to conclude that the hydrodynamic behaviour of the melt pool and ingot solidification process can be greatly influenced by such an ensemble arc macroscopic motion.

In order to confirm the previous statements, the dynamic behaviour of the arc in an industrial VAR furnace has been investigated. Two synchronized video cameras positioned in front of diametrically opposite viewing glasses on top of the furnace chamber were used to film the annulus gap between the electrode and crucible wall. Video images were recorded during the melt of a Zy2 ingot with various stirring conditions.

To help interpreting the recorded films, an image processing procedure similar to that proposed by Ward et al. [21] was developed. First, each film was split into a series of images. Then a 2 s moving average was applied to suppress high frequency fluctuations related to individual cathode spot behaviour and the sampling frequency was reduced to 5 frames/s. A given region of interest was extracted from each image and all the results were put side by side to build a temporal sequence (Figure 4, *a*). Finally, the luminosity in the extracted region was quantified and a Fourier analysis was performed to determine the frequencies of fluctuations along the sequence.

An example of two sequences corresponding to diametrically opposite regions is illustrated in Figure 4, *b*. A plot of the evolution of the luminosity for both sequences is also shown on the Figure. The luminosity fluctuates quite regularly, with an alternation between very bright time periods and other time periods during which it is notably reduced.

The fluctuations of luminosity in the two diametrically opposed regions are essentially in phase opposition. A frequency analysis indicates that these fluctuations involve several periods, with a dominating period of the order of 30 s, identical for the two cameras. These fluctuations may be related to the arc behaviour. Indeed, it

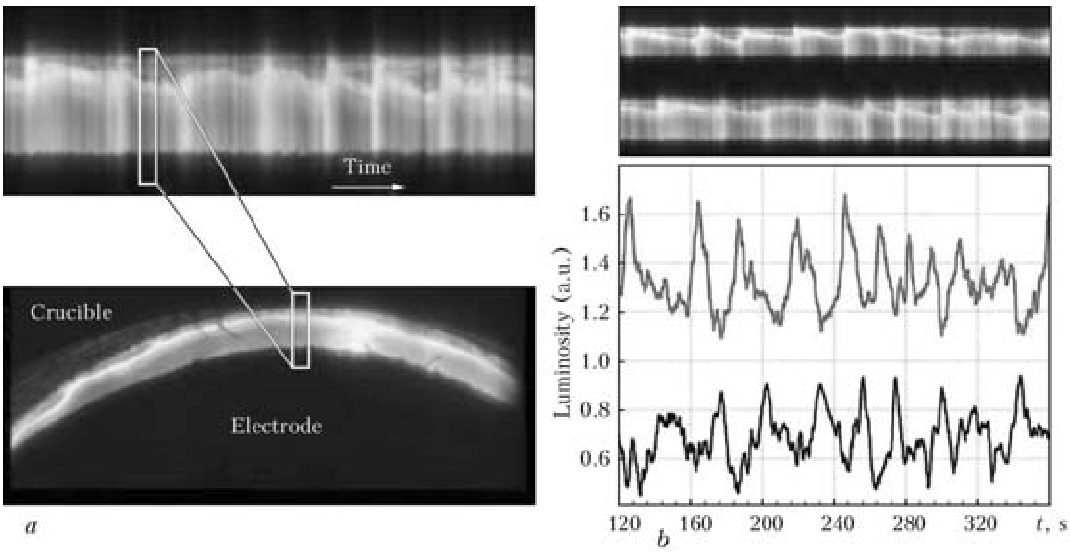

Figure 4. Temporal sequence used to study the fluctuations of luminosity above the ingot (*a*), typical temporal sequences obtained for two diametrically opposite regions (*b*)

can reasonably be considered that the luminosity fluctuates as a consequence of the evolution of the spatial distribution of the arc, whose centre of gravity moves across the electrode surface with a period of about 30 s. This phenomenon was observed for all the melt conditions tested. The dominant period of the fluctuations was of the same order of magnitude for all melt conditions (including the conditions without any stirring). It seems in particular to be unconnected to the reversal period of the magnetic field. Thus, an ensemble motion of the arc seems to exist for all operating conditions and it appears to be relatively independent of the presence of an external axial magnetic field.

This work enables us to confirm the conclusions reached by Ward et al. [22] who reported a value of the time constant of the arc motion very similar to the one determined here. As discussed previously, the existence of a slow motion of the arc centre (with a time period of around 30 s) could have important implications for the modelling of the VAR process.

Electromagnetic stirring and macrosegregation in VAR zirconium ingots. Despite the use of electromagnetic stirring, chemical heterogeneities develop in the mushy zone during the solidification stage. One of the main challenges for Zr and Ti producers is to master the VAR process in order to control the macrosegregation in remelted ingots. Macrosegregation results from the association of microsegregation and transport phenomena. The latter are primarily due to the flow in the liquid and mushy parts. It is now well established [24, 25] that the hydrodynamics of the melt pool depends on the combined action of the followings: thermal and solutal buoyancy, self-induced electromagnetic force and the periodic centrifugal force caused by the angular movement generated by the stirring. The aim of this section is to investigate numerically the action of these forces on the macrosegregation of Zircaloy 4 VAR ingots.

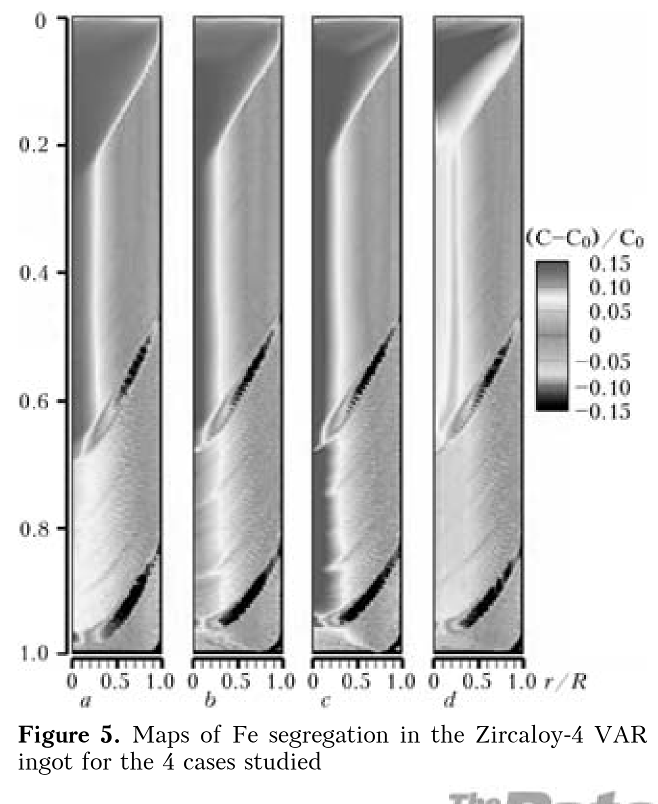

Figure 5. Maps of Fe segregation in the Zircaloy-4 VAR ingot for the 4 cases studied

In order to improve the description of the solidification and related macrosegregation, a multiscale model has been recently incorporated into SOLAR to simulate the solidification of multicomponent alloy VAR ingots. It is based on a volume-averaged Euler-Euler two phases formulation [26, 27]. At the macroscopic level, the permeability of the mushy zone is given by the Carman-Kozeny law, depending on a microstructure dimension typically of the order of the secondary dendrite arm spacing (SDAS). A macroscopic k-ε model that takes into account the actions of both the thermosolutal buoyancy and the influence of the solid phase in the mushy zone is used to simulate the turbulent nature of the flow. The phase change is treated locally at the microscopic level, either by assuming the lever rule or accounting for grain growth controlled by finite diffusion of alloy elements in both liquid and solid phases.

A Zy4 electrode was remelted in a production furnace. Two stirring sequences were successively applied: a strong alternated stirring followed by a weak continuous one. In addition, a continuous and strong stirring was temporarily used in order to mark several melt pools in the ingot. The recording of the actual operating process parameters provided input data for the model.

Thermosolutal buoyancy effects are simulated thanks to the Boussinesq approximation. Thermal and solutal expansion coefficients for Zr alloys are not available in the literature. Nevertheless, the thermal expansion coefficient β_T was estimated from data on pure liquid Zr. To investigate the influence of solutal convection caused by Sn concentration gradients (Sn is the major alloying element in Zy4), we have simulated 4 cases:

(a) $\beta_T = 0$, $\beta_S^{Sn} = 0$;

(b) $\beta_T > 0$, $\beta_S^{Sn} = 0$;

(c) $\beta_T > 0$, $\beta_S^{Sn} < 0$ and

(d) $\beta_T > 0$, $\beta_S^{Sn} > 0$.

The positive value of the solutal expansion coefficient β_S^{Sn} (case d), was calculated from the volume additivity assumption. The other value (case c) was intentionally negative. Case a corresponds to the absence of all thermosolutal buoyancy, which means that the flow is only caused by the electromagnetic stirring.

For the four cases, the final maps of Fe segregation computed by the model are shown in Figure 5. Because of the application of two successive stirring sequences, two main segregation patterns can be observed along the ingot height. In addition, we can see two inclined depleted bands caused by the pool markings. The enriched zone at the top of the ingot was caused by the solidification of the last melt pool. The average concentration of Fe in the liquid pool increases as the ingot grows because its partition coefficient is less than unity.

When thermosolutal buoyancy is not accounted for (case a), the model predicts an iron enrichment in the ingot central zone whatever the stirring employed. Actually, the centrifugal force due to the angular flow is predominant and generates a clockwise flow cell. Consequently, iron-enriched liquid accumulates at the bottom of the melt pool and in the mushy zone, causing a positive segregation near the axis. Alternated stirring causes a weaker radial macrosegregation than unidirectional stirring.

For both stirring practices, accounting for thermal convection (case b) increases slightly the radial macrosegregation of the ingot central part, as thermal buoyancy strengthens the centrifugal force. In the mushy zone, the consequence is a more intensive circulation resulting into more transport of enriched liquid towards the centerline.

The effect of solutal convection on the centerline macrosegregation is visible on Figures 5, c and d. In case (c), radial segregation close to the centerline is notably amplified because all the volumetric forces cooperate. On the opposite, in case (d), the solutal buoyancy is counteracting and reverses the flow in the mushy zone at the bottom of the pool. The counterclockwise upward flow in the mushy zone reduces the segregation in the central region. When stirring is alternated (bottom half of the ingot), iron concentration is roughly uniform while a continuous stirring (ingot top half) results in a positive segregation band located at $r/R \sim 0.25$ (R is the total radius of the ingot). This band forms due to the small counterclockwise flow loop induced by the solutal convection, which carries iron-rich liquid from the center to the outward radial direction.

The Fe segregation profiles predicted by the model clearly show that thermosolutal convection affects the macrosegregation only in the central region. In the upper part, chemical analyses show the Fe content rises continuously in the inner half of the ingot. Comparison with the model predictions reveals that such a behaviour is characteristic of case (d) where thermosolutal buoyancy is considered and $\beta_S^{Sn} > 0$. This shows that the upward flow driven by solutal buoyancy effects is partially responsible of the macrosegregation in Zy4 VAR ingots. In the outer part, where the centrifugal force is predominant, model and experimental results are in good agreement.

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Received 09.04.2013

RESEARCH IN JOINING TECHNOLOGIES IN AUSTRIA

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Within the Austrian network of excellence COMET K-project JOIN4+ companies and research institutes cooperate in funded research projects. JOIN4+ exhibits a total budget of 6.6 Mio. Euros, which is covered by all research partners, the Austrian government as well as the involved provinces. Currently eight different projects in two areas are treated. In this contribution the funding situation as well as selected results are presented. 11 Ref., 7 Figures.

Keywords: *research funding, welding, friction welding, FSSW, modelling, AHSS*

Innovative and competitive products require sound basic research with according budgets. As one positive example the Austrian Network of Excellence for Joining Technologies JOIN4+ is presented in this contribution. International partners from industry and academia in the field of welding technology cover relevant tasks enabling the company partners to introduce innovative products on the global market.

Funding concept. The Austrian Research Promotion Agency (FFG) offers different concepts for co-financing of application-oriented research. The current COMET-program (Competence Centres for Excellent Technologies) contains three different routes (K2, K1 and K-projects) which covers different aims, budgets and contract periods [1].

K-projects are focused on the application, which is very attractive for companies. Nevertheless compared to K1 and K2, K-projects show the smallest overall budget.

Basic guidlines Within K-projects company partner have to finance 50 % of the project volume by means of in-kind or cash contribution.

5 % of the overall budget has to be covered by the research partners by means of inkind contributions. Two third of the residual is funded by the as fore mentioned FFG and one third is covered by the involved provinces of Austria. The maximum possible funding is limited for each K-project.

Projects and partners. Within the K-project JOIN4+ 15 company partners are actively involved in eight different projects. Two partners are from Germany, one is from Switzerland, the remaining are from Austria:

✧*Company partners*:

- Air Liquid Austria GmbH;
- Audi AG;
- Berndorf Band GmbH;
- Bombardier Transportation Austria GmbH;
- Benteler SGL Composite Technology GmbH;
- Fronius International GmbH;
- InfraTec GmbH;
- Jansen AG;
- MCE — Maschinen und Apparatebau GmbH & Co;
- pewag austria GmbH;
- PLASMO Industrietechnik GmbH;
- Wilhelm Schmidt KG;
- voestalpine Draht GmbH;
- voestalpine Stahl GmbH;
- Welser Profile AG.

Five scientific partners from Austria and one from Germany are completing the project team:

✧*Research partners*:

- Johannes Kepler University Linz, Institute for Communications Engineering and RF-Systems;
- Fraunhofer Institute for Mechanics of Materials;
- Graz University of Technology, Institute for Materials Science and Welding;
- Vienna University of Technology, Institute of Materials Science and Technology;
- Light Metals Technologies Ranshofen;
- Schweisstechnische Zentralanstalt Wien.

In each subproject at minimum two companies and one research partner have to be involved. One requirement of this research funding approach is the strong link between different subprojects leading to a significant added value compared to single projects.

As shown in Figure 1 different sub-projects within JOIN4+ are coupled to each other. Additionally to informal information exchange, seminars and other activities are organised by the JOIN4+ management.

Due to different focus of the diverse projects tow clusters were formed. These areas are called Advanced Materials Joining focusing on the behaviour of the material to be joined and Advanced Joining Processes & in-situ Process Control concentrating on advanced joining processes. Additionally, modelling and simulation is applied to all projects and a strategic project is run within JOIN4+.

Organisation. The Institute for Materials Science and Welding at Graz University of Technology in Austria is the responsible consortium manager. Different persons in charge cover scientific, financial and operative tasks. To consider and protect different interests of scientific and company partners, the core partners are joined in the legal consortium ARGE JOIN4+, supporting the consortium management.

Boundary conditions. Additionally to the funding contract each individual sub-project is defined by a project contract determining tasks, responsibilities and intellectual property rights between the partners. Funding is paid annually based on the given cost report.

For documentation, annual reports have to be forwarded to the funding organisation. These reports also include success stories. Additionally the K-project is evaluated after two years and after the end of the funding period. As a result of these evaluations changes and advancements can be requested by the funding organisation.

Depending on the requirements of the involved provinces additional efforts are necessary such as the formulation of a marketing concept or the setup of a homepage.

Selected results. *Soft zone*. The soft zone due to welding of advanced high strength steels often is a limiting factor in the application of these materials (Figure 2).

In this sub-project it is systematically investigated, which welding parameters are essential in the development of this weak zone and how they change the local material properties. Furthermore it is explored, which variables, describing the soft zone, significantly influence the strength of a real joint. Basically the static strength is investigated but also the fatigue strength is considered.

Therefore extensive experimental thermo-mechanical investigations are performed to evaluate the numerical finite element simulation using Abaqus solver. [3] The systematic variation of different variables describing the soft zone shows that especially the quotient of width of the soft zone and sheet thickness as well as the level of the soft zone compared to the strength of the base materials are the most influencing factors. However preparation of the seam, especially of the bevel angel, was found to be less important.

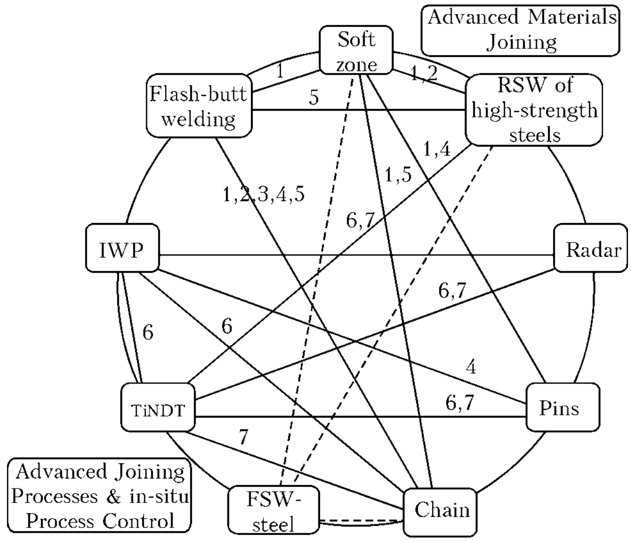

Figure 1. Coupling of different sub-projects covering different topics

Additionally microstructure development due to welding is modelled by means of SYSWELD. In house developed routines are implemented to consider effects like grain growth. [4] Variables necessary in these routines are based on microstructural characterisation of different treated microstructures by means of metallography. The results are then verified and extrapolated by use of MatCalc simulations. With this coupling of different methods it is possible to calculate the grain size and therefore to estimate material's strength due to an applied welding process.

Chain. In a predecessor project a prototype for a totally new approach in chain production was designed. Two half links are welded by means of linear friction welding. [5] In the current sub-project the influence of different welding parameters such as amplitude, frequency, friction force and forging force on the quality of the joint is investigated systematically. It is found that the geometry of the flash is a reasonable indicator for the quality. This correlation enables very fast inline quality estimation during the start-up phase of the process. Furthermore it is found that with decreasing welding cycle time the quality

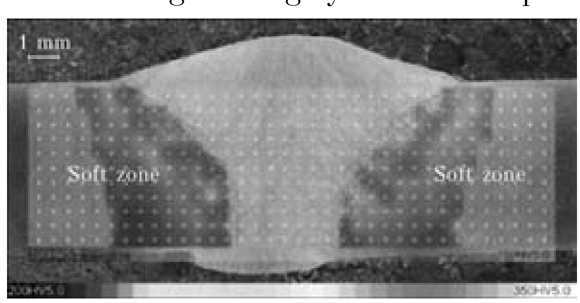

Figure 2. Soft zone due to welding of high-strength steel [2]

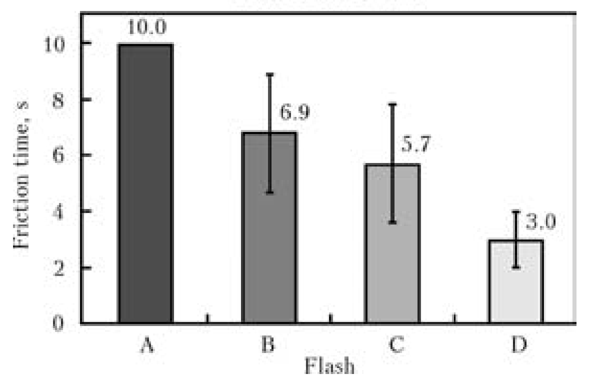

Figure 3. With decreasing friction time the joint quality improves. Quality is estimated by means of flash geometry from not acceptable (A) to very good (D)

of the joint improves. Based on this it is concluded could that this new production process is highly economic (Figure 3).

Additionally to comprehensive experimental investigations of the friction welding process of chains, a simulation program of the process is developed. A sever difficulty is the proper description of the heat input, which is based on friction and significantly changes during the process. By means of an inverse approach both heat input and temperature dependant friction coefficient is estimated. Therefore the local temperature of the chain, as an input parameter for this calculation, has to be measured as a function of time.

With the estimated heat input as a boundary condition the transient temperature field and subsequently deformation as well as flash formation can be calculated by means of an FE code, see Figure 4 [6].

Pin structures. Applying the CMT process (Cold Metal Transfer) developed by Fronius it is possible to produce different geometries of so called pins, as shown in Figure 5.

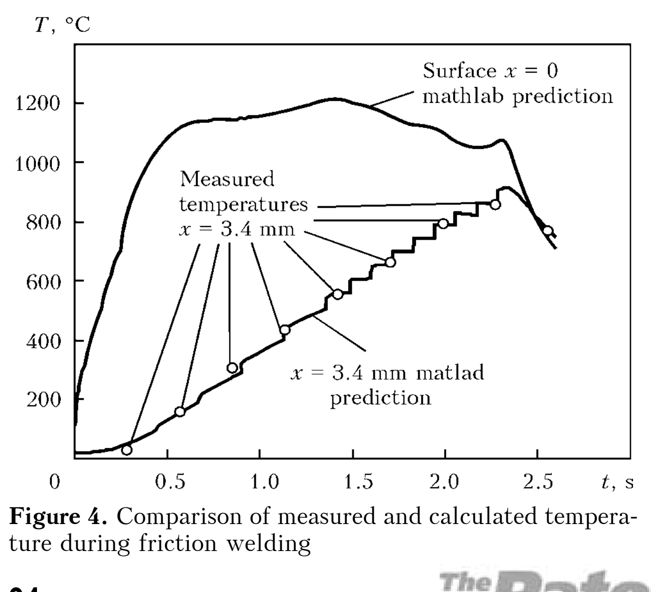

Figure 4. Comparison of measured and calculated temperature during friction welding

By proper application of voltage and mechanical movement of the filler wire the height and shape of the pin can be determined.

Using such pins enables to strengthen the joints between dissimilar materials such as steel and aluminium or even metal and fibre reinforced polymers by form-fit [7].

In this project two different goals are defined. In a first step the production process of the pin itself is modelled. Especially heat input distribution during welding and shaping of the pin is modelled in a coupled FE calculation for different materials such as steel, titanium aluminides, etc. Secondly, the properties of the pins in combination with the materials to be joined are estimated. These properties depend on a high degree on the process of welding and shaping which is performed prior to the mechanical loading.

Aluminium pins face a special challenge for a successful application. Based on the thermophysical properties they cannot be produced shorter than approximately 2mm. Since one possible application is automotive industry where thin sheets are of interest, even 2mm pins seem to be too long. Therefore one current focus in research is to produce much shorter pins for aluminium.

Based on the Surfisculpt® process, which was developed by TWI for steel, electron beam process is applied to structure the surface of aluminium thin sheets (Figure 6). This approach has not been reported for aluminium alloys so far.

Friction stir spot welding (FSSW) of AA6082-T6. Additionally to the sub-projects that have been submitted, proved and funded by the COMET program, there is a further possibility to finance basic research projects in the so-called non-k area, where the company partners directly finance strategic projects. One topic under consideration deals with the modelling of microstructure evolution of aluminium alloys during the friction stir spot welding process.

Based on previous projects [9, 10] a physically based model developed to describe the microstructural evolution due to FSSW [11]. To generate proper material input parameters for the simulation, Gleeble experiments are conducted with a torsion unit. The grain size representing the thermo mechanical heat affected zone is measured from specially defined welding experiments. These results are then used to evaluate the simu-

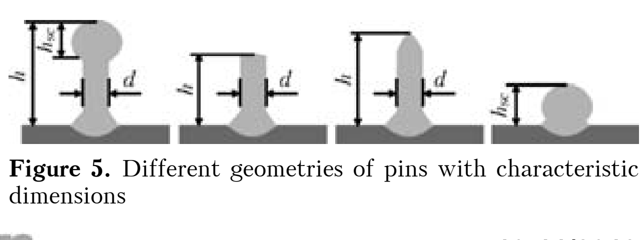

Figure 5. Different geometries of pins with characteristic dimensions

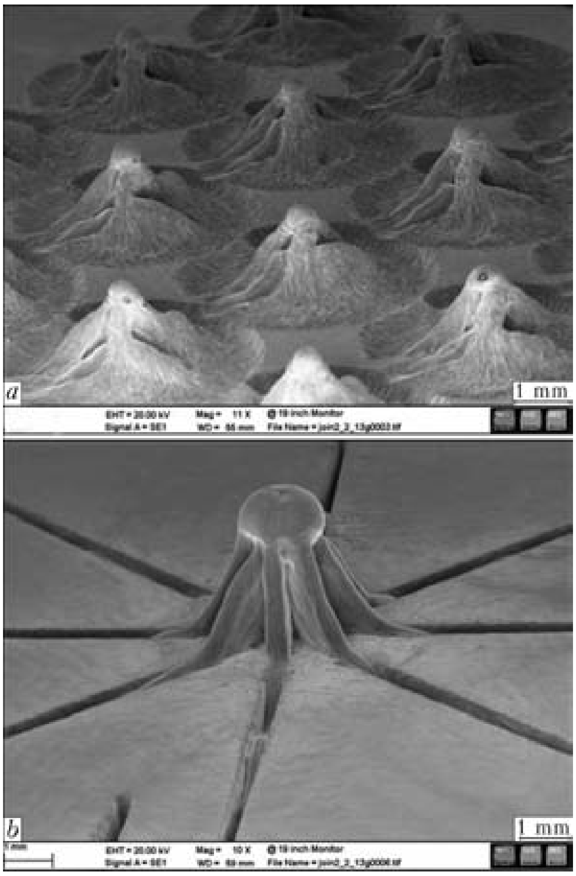

Figure 6. Surface structuring by pins (*a*) is produced from base material by electron beam introduced material flow (*b*)

lated thermo mechanical heat affected zone by means of the calculated grain size distribution, see Figure 7.

Summary. The Austrian K-project JOIN4+ is a very successful cooperation between companies and academia. In two working areas eight different projects with significant interconnections are treated. Following key issues can be summarized:

- Basic mechanisms of friction welding;
- Prediction of properties of welded joints in advanced high strength steels;
- Improved reliability for detection and characterisation of weld defects;
- Improved process reliability by control of significant welding parameters;
- Development of modern sensors for welding processes;
- Joining of dissimilar materials.

Sound communication between the project partners stimulates to find surprising solutions leading to innovative and advanced results. A further advantage of this approach is the possible starting point of a long-term cooperation between acting partners.

Figure 7. Comparison of experimentally and numerically determined thermo mechanical affected zone after FSSW of AA6082-T6 [11]

Acknowledgement. *The K-project Network of Excellence for Joining Technologies JOIN4+ is funded in the frame of COMET — Competence Centers for Excellent Technologies by BMVIT, BMWFJ, FFG, Land Oberssster-reich, Land Steiermark, SFG and ZIT. The program COMET is managed by the Austrian Research Promotion Agency in Vienna.*

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Received 22.02.2013

ONGOING ACTIVITIES AND PROSPECTS RELATED TO WELDING TECHNOLOGY AT LAPROSOLDA–BRAZIL

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An overview of Laprosolda' activities in research, development and innovation of welding processes is presented within three main areas: fundamentals, instrumentation and application. Since the group philosophy aims to develop different welding processes, in this work three cases are presented to illustrate these areas. The first one deals with the measurement of heat input for derivative arc-welding processes. The second case shows embedded systems developed for arc-welding monitoring and control. The last one presents the evaluation of conventional and controlled short-circuit GMAW processes for pipe welding. The objective is to present the ongoing activities and prospects related to welding technology within Laprosolda group. 16 Ref., 3 Tables, 10 Figures.

Keywords: *heat input measurement, monitoring and control, pipe welding, ongoing activities, prospects*

Welding technology demands continuous research, development and innovation through the years. It is defined by ISO 3834 (2005) as a special manufacturing process, since quality assurance cannot be realized by final inspection only. The joining is totally dependent on personnel, equipment and facilities. Therefore, development and improvement of equipment and methods are needed for constant development.

In this context, the Brazilian group named Laprosolda (Center for Research and Development of Welding Processes) started its activities in research, development and innovation of welding processes in 1992. The group philosophy aims to develop different welding processes in three main areas (or work line) named: the Fundamentals of Welding (arc physics, metal transfer during derivative processes, corrosion in welded joints, derivative arc-welding processes and numerical simulation of heat transfer, residual stress and distortion correlated to welding processes), instrumentation for arc-welding processes (remote monitoring and controlling for arc welding, embedded wireless monitoring system, low-cost vision system, calorimeters, sound monitoring system, waveform synchronized weaving, development of dedicated experimental rigs and luminescence sensors for AVC and joint tracking) and Application (pipe welding of API steels and CRA, overlaying for wear and corrosion purposes, RSW for AHSS in MFDC and AC machines, stainless steel weldability and health and safety — fumes, radiation and electromagnetic fields).

The objective of this work is to summarize the activities that have been done and what is intend to do in the future in Laprosolda group within the scope of these three areas. In order to illustrate these activities, three following cases are presented. The first one deals with the measurement of heat input for derivative arc-welding processes. The second case shows embedded systems developed for arc-welding monitoring and control. The last one presents pipe welding with conventional and derivative GMAW processes.

Heat input measurement for derivative processes. One of the most influent parameter on the welding process is the heat delivered to the workpiece (heat input) due to its direct connection with changes in metallurgical characteristics and mechanical properties of the weld joint. In order to quantify the heat input, different methods have been developed, both theoretical (analytical and numerical ones) and experimental (calorimetry), with large dispersion of results.

Calorimeters used for thermal studies in welding include different methodologies and physics basis for their construction and with, technological advances, calorimeters increase in sophistication. The last trend is the use of liquid-nitrogen calorimeter (Pepe, 2010), which is based on the measurement of evaporated mass from a recipient with liquid nitrogen and this mass is correlated to the heat input. Although liquid-nitrogen (N2L) calorimeter is a powerful tool for heat input measurement, it was not found in literature any attempt in automatize or take external effects into account.

Therefore, a fully automatic N2L calorimeter (Figure 1) was developed at Laprosolda basing on pneumatic automation for measuring heat input during different arc-welding processes, with improvement from previous literature work, minimizing the influence of operator, environment, welding time and transfer time (from rig to N2L recipient). Very good repeatability was found with maximum data scattering of 3.0 %.

Due to the increase importance of derivative GMAW processes, their thermal efficiencies were measured. These processes are surface tension transfer (STT), regulated metal deposition (RMD), cold metal transfer (CMT), GMAW-P (Pulsed) and GMAW-VP (Variable Polarity). It must be pointed out that the correct nomenclature to designate such variants is GMAW process with controlled short-circuit metal transfer by using commercial RMD/STT/CMT power sources manufactured by Miller/Lincoln/Fronius». This nomenclature is usually summarized in the form of RMD/STT/CMT Process in order to simplify both oral and written communication.

Welding parameters were adopted from previous Laprosolda researches (Vilarinho et al., 2009 and Costa, 2011) and preliminaries runs were carried out to select proper parameters at two current levels of 115 and 155 A. ASTM A36 plates were used with 1.2 mm AWS ER70S-6 wire and Ar + 25 % CO_2 (short-circuit) and Ar + 5 % O_2 (spray) as shielding gases. Data acquisition was carried out for monitoring voltage, current, wire feed speed and mass (scale read out) at 2.0 kS/s. Welding energy calculation was performed by Equation 1. The heat input is calculated by latent heat of N2L and thermal efficiency is calculated by dividing heat input by welding energy.

$$P_{\text{inst}} = \frac{\sum_{i=1}^{n} U_i I_i}{n}, \qquad (1)$$

where Pinst is instantaneous power, W; U_i is voltage for each i sample acquired by DAQ system, V; I_i is current for each I sample acquired by DAQ system, A; and n is the number of samples. This power must be also divided by the travel speed.

The results are shown in Table 1. It must be pointed out that this table shows one replica for each condition to show repeatability. It is possible to observe the higher values of electric power (and therefore welding energy) for GMAW-P and GMAW-PV (Figure 2). This is due to the fact that these processes demands free-flight transfer mode, i.e, they demand high arc lengths and therefore higher voltages when compared to the other processes (STT, RMD and CMT), which uses controlled short-circuit transfer.

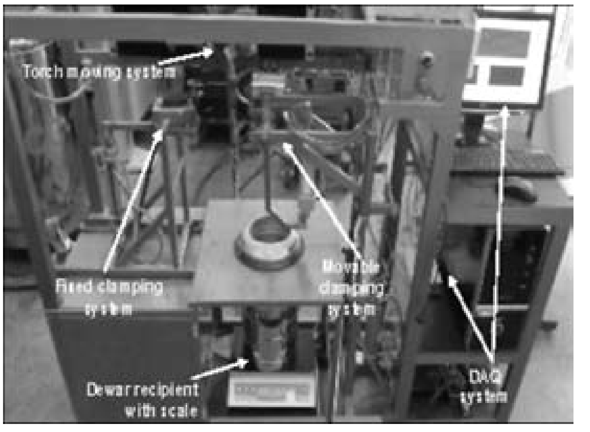

Figure 1. Experimental rig for N2L calorimeter

For STT process the measured values for thermal efficiency range from 74.0 to 78.7 %, when current arises from 115 A to 155 A. This shows an increase in heat losses by convection and radiation. The average thermal efficiency for STT is 76.4 %, which is low when compared to 85 % presented by other authors (Hsu and Soltis, 2003 and Pepe, 2010). For CMT process, Pepe (2010) presents average value of 86 %, which is also higher than the ones found in this work: 75.4 % for 115 A and 76.8 % for 155 A. The reason for this discrepancy is the range of parameters used here and other authors, and the fact that welding time for these authors are considerably lower (25 s for literature and 42 s in this work).

During RMD process, thermal efficiencies of 91.0 and 76.3 % were measured for 115 and 155 A, respectively, i.e., a similar behavior was found when compared to other processes. Measurements from other authors were not found in literature and since these results are close to the ones measured for STT and CMT, they are considered to be adequate. The main reason for such close measured values for thermal efficiency is due to the fact that the welding parameters were previously investigated (Costa, 2011) and represent an optimized condition for these three processes (STT,

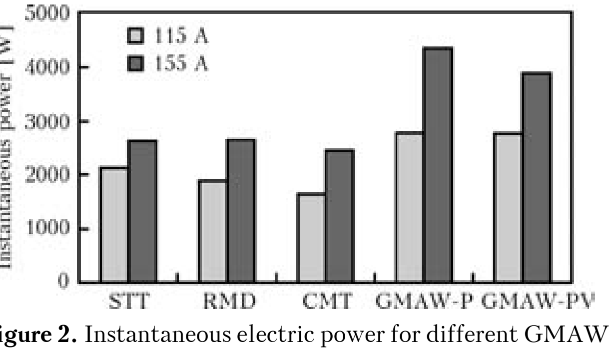

Figure 2. Instantaneous electric power for different GMAW processes

Table 1. Measurements by using the N2L calorimeter for derivative processes

I, A	WFS, cm/min	V_s, cm/min	L_c, cm	U_m, V	I_m, A	P_{inst}, W	E_{sold}, J/mm	E_{imp}, J/mm	R_{end}, %
STT									
115	2.3	12.3	15	18.4	119	2147	1055	774	73.4
115	2.3	12.3	15	18.4	119	2134	1045	780	74.7
155	3.3	17.6	15	16.6	154	2606	851	681	79.9
155	3.3	17.6	15	16.6	154	2629	892	692	77.5
									76.4
RMD									
115	2.3	12.3	15	17.5	118	1906	903	741	82.0
115	2.3	12.3	15	17.5	118	1917	902	722	80.1
155	3.3	17.6	15	17.5	156	2651	957	730	76.3
155	3.3	17.6	15	17.6	154	2645	944	720	76.2
									78.6
CMT									
115	2.2	11.2	15	10.7	114	1646	861	649	75.4
115	2.2	11.2	15	10.9	113	1658	863	652	75.6
155	3.3	17.0	15	12.0	156	2464	816	622	76.3
155	3.3	17.0	15	11.9	157	2465	851	657	77.2
									76.1
GMAW-P									
115	3.0	15.8	15	21.2	113	2773	1049	744	70.9
115	3.0	15.8	15	21.5	113	2816	1031	725	70.3
155	4.0	21.3	15	25.7	154	4368	1184	813	68.7
155	4.0	21.3	15	25.3	155	4360	1180	812	68.9
									69.7
GMAW-PV									
115	3.0	15.8	15	21.9	115	2775	1462	860	58.9
115	3.0	15.8	15	22.1	115	2793	1512	867	57.3
155	4.0	21.3	15	23.7	154	3898	1408	816	57.9
155	4.0	21.3	15	23.8	154	3922	1394	808	57.9
									58.0

RMD and CMT) for a given situation (welding of carbon-steel pipes in single pass).

GMAW-P process presented a decrease in thermal efficiency from 70.6 to 68.8 % when current decrease from 115 A to 155 A, which again indicates a higher heat loss for higher currents and a demand for higher arc voltage. The latter contributes to a higher heat input. The average value of thermal efficiency for GMAW-P found in literature (Joseph et al., 2003) varies from 62 to 73 %, against 69.7 % in this work and in Bosworth (1991), which reports values from 75 to 80 %.

Among the GMAW processes, GMAW-PV is the one that presented the lowest thermal efficiency with an average of 58.0 %, with no statistical variance between current levels (115 and 155 A). Harwig (2003) reports that the heat input by GMAW-PV is at least 25 % lower when compared to GMAW-P and almost half when compared to conventional spray transfer for a given wire feed speed.

Embedded systems for monitoring and control. Different devices from different manufacturers provide monitoring for welding process, with focus on specific parameters. Ongoing trend follows the creation of equipment for practical and simple use, with the elimination of adaptive circuits and greater flexibility. This is highlighted by the fact that the monitoring equipment must be adapted to the manufacturing environment and not otherwise. The demand for flexibility is

Table 2. Comparison of resolution for different resolutions of A/D converters

Parameter	Range	Required resolution	A/D 10 bits	A/D 12 bits	A/D 14 bits
Voltage, V	±100	0.1	±0.196	±0.048	±0.012
Current, A	±500	1	±0.978	±0.244	±0.061

accomplished by replacing traditional cabling system by wireless communication one, which is not readily available/applicable for welding monitoring.

The initial idea of an embedded device (complete and independent system prepared to perform a unique and determined task — Cunha, 2007) with wireless communication is originated in the dissemination of computer networks for manufacturing and technological development of communication products and portable data (notebooks and smartphones). This scenario indicates the integration of welding monitoring with wireless communication, which is an achievable reality and promising technology. Therefore, it is presented a series of independent embedded («autonomous») systems with specific features (proprietary technology, scalability, portability, autonomy, flexibility and low cost/simplicity of operation), namely:

- wireless signal monitoring;
- vision-based joint tracking;
- waveform synchronized weaving;
- sound monitoring for regularity index determination.

The first one is a system for wireless arc-welding signals monitoring (so-called MoSo — Welding Monitor in Portuguese, Machado, 2011), which consists of an independent embedded system, capable of monitoring arc-welding processes and communicating in a robust and flexible way to different devices, with a user-friendly system, using the state-of-the-art in communication technology. It employs an A/D converter resolution of 12-bit (Table 2) with the Microchip ZeroG ZG2100M for Wi-Fi communication module and the dsPIC33FJ256GP710 as the device to be used.

The human interface of MoSo system is based on web server technology and it is accessible by any equipment with a built-in web browser. The main page of the system has a configuration section, where the user selects among fixed acquisition time (0.5 to 4 s), finite and continuous acquisition, and the possibility for data saving.

Once initiated, MoSo receives the data from the embedded system and shows waveforms for voltage, current and wire feed speed. It also shows the rectified mean and RMS (root mean square) values of each parameter. The whole system was tested with GMAW short-circuit and spray, GMAW-Pulsed, GTAW-AC (alternating current) and GTAW-Pulsed. Using the statistical parameter knows as Pearson coefficient (r), the waveforms saved by MoSo where compared to a reference system (from a worldwide manufacturer of DAQ systems), and shows results above 0.7, indicating a strong correlation between the waveforms. The rectified mean and RMS values obtained show relative errors below 2.5 %, which is required by BS7570 (2000). As an example, Figure 3 presents a comparison between the results (waveforms) from MoSo system and reference one for GMAW with short-circuit transfer. The resemblance between the obtained signals from both developed and reference systems is evident. Therefore, the developed system met its objective and it is capable of performing the required tasks.

The second system is a low-cost vision system, which is based on the use of high-power (70 W) laser diodes with low cost. It can be used for man-assisted supervision, for joint tracking and for process parameter control, such as arc length and weaving amplitude. The developed vision system is so-called ViaSolda and consists of an analogic low-cost camera (CCD Costar SI-M331) with low exposure time (1.25 μs) and resolution of 768 × 494 pixels. Also ViaSolda system uses a developed near-infrared (905 nm) illumination set that consists of 19 high-power laser diodes (Osram SPL PL90_3). It also has a high power circuit and a programmable MCU (microcontroller) capable of generating enough power to the

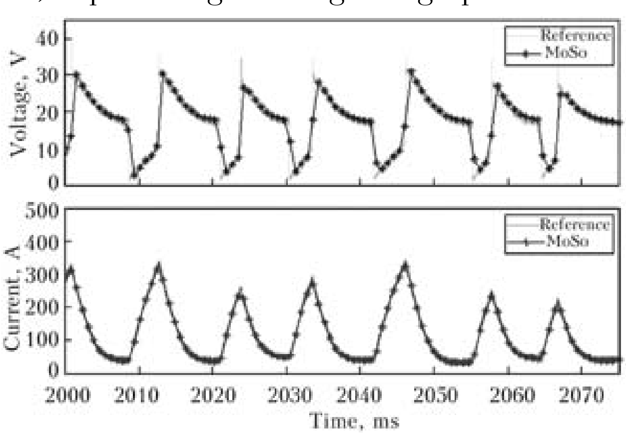

Figure 3. Current and voltage signal obtained by using MoSo and reference system: 19.0 V; 4 m/min, Ar + 25 % CO_2 and 1.0 mm ER70S-6 electrode

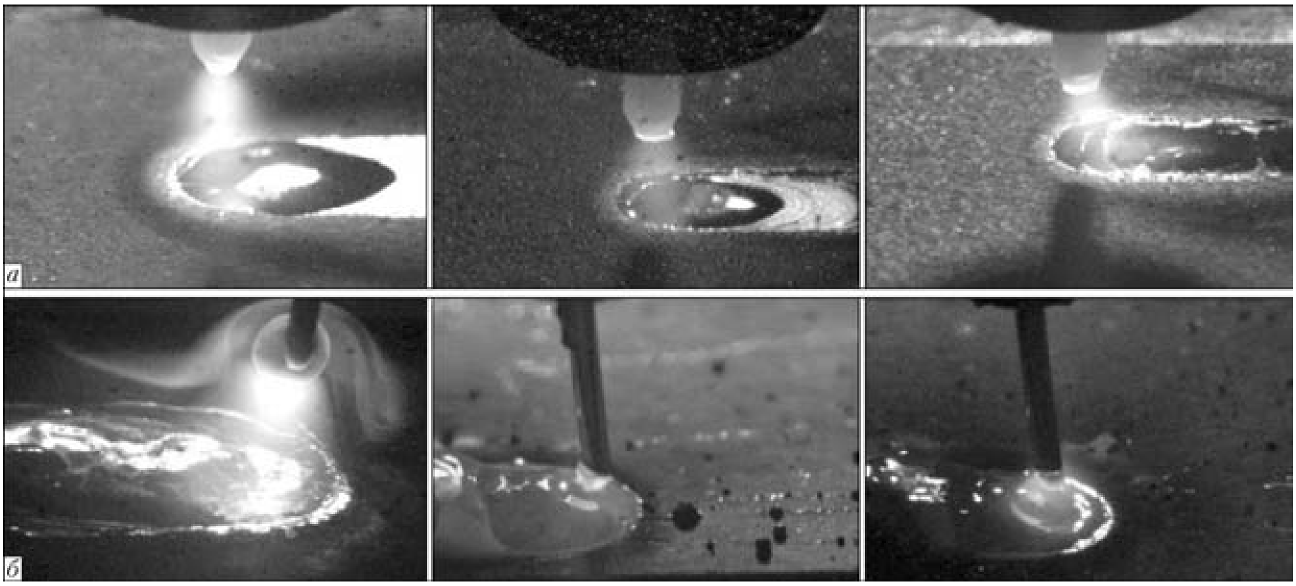

Figure 4. ViaSolda system images from left to right: *a* — GTAW at 250, 150 A (shorter exposure) and 150 A (longer exposure); *b* — GMAW at 150 A for globular transfer (30 V), short-circuit transfer during short-circuit (18 V) and short-circuit transfer during open arc (18 V)

diodes and an electronic trigger to turn the camera on (shuttering) and the illumination system at the same time. In this case a frequency of 30 Hz (frames per second) was selected (Mota, 2011).

The images obtained by ViaSolda are shown in Figure 4. It is possible to assert that the developed low-cost vision system is fully capable of viewing the weld pool and its surrounds and, therefore can be used as a vision-based joint tracking system.

The third proposed system is an embedded and dedicated system capable of monitoring the torch angles (attack and working angles) during torch movements (travel speed and weaving). By using the measurement of the torch angle, the system can control the power source and lead to different set of parameters (in the present version, three different sets are possible). This is underlined by the requirements of field joining, which involve variability in geometry, consumables, equipment, personnel skills, land site and weather. Among those, the tolerance of the groove itself is a major concerned when mechanized welding is performed. Therefore, it is important to develop strategies that can cope with poor geometric tolerances, which are estimated from 1.6 to 3.0 mm for both root opening and alignment of the groove. One possible strategy for overcoming this limitation is the use of synchronous waveforms with torch positioning during its weaving. The idea is to vary welding parameters, such as positive to negative polarities or high to low currents, dependently to the waving setup, as shown in Figure 5. Also different waveforms can use, since they are synchronized with weaving.

Therefore, it was developed and assessed a system Conparte (Parameter Control System by Weaving, in Portuguese), which is capable of monitoring the torch angles (attack and working angles) during torch movement (travel speed and weaving). During the weaving three regions are considered (as shown in Figure 5) and numbered 1–3. Once each of these regions is identified, the Conparte system commands a welding power source (IMC DIGIPlus A7) to select a specific welding program. The identification of each spatial region can be done by different sensors. In

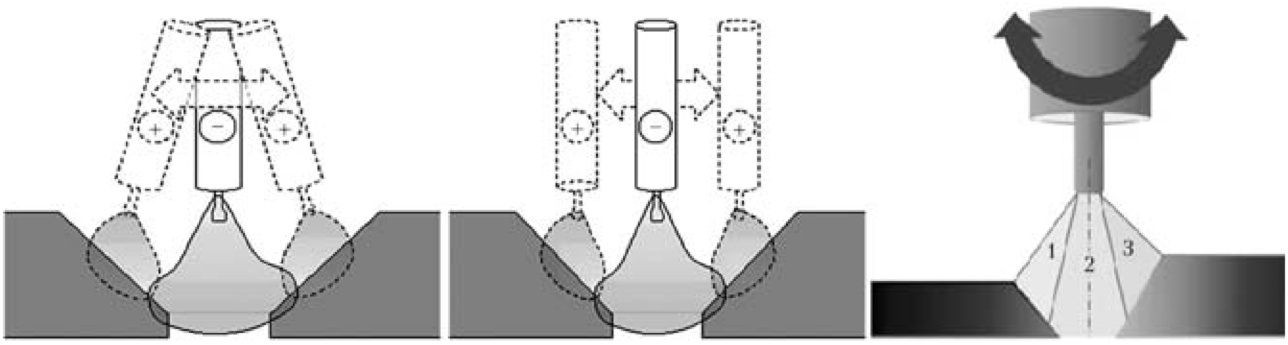

Figure 5. Different conceptions of synchronous weaving

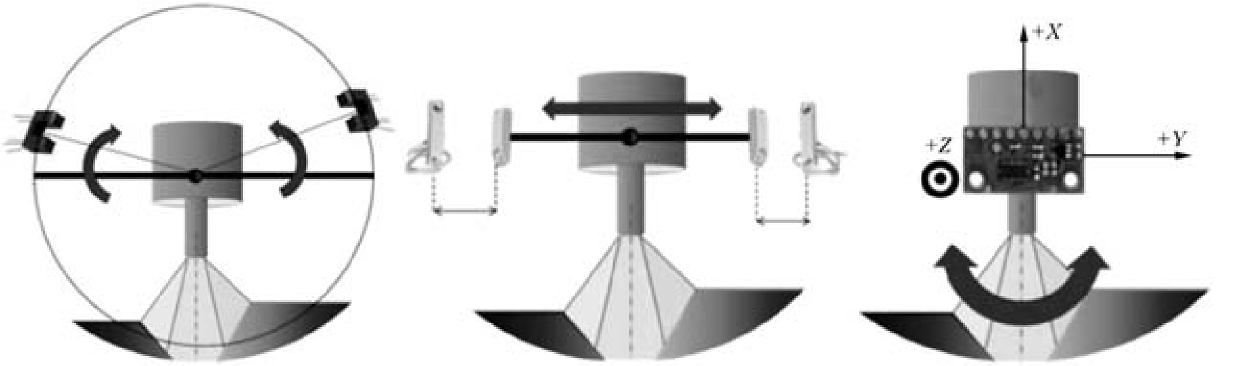

Figure 6. Sensors used in Conparte system: magnetic 9028PA (*left*), optic infrared receiver TCST1103 (*center*) and accelerometer MMA7361L (*right*)

this case, a three-axis accelerometer (MMA7361L), a magnetic-contact sensor (9028PA) and an optic infrared receiver (TCST1103) were used (Figure 6). As mentioned, it identifies three mentioned regions and set three different programs in the power source, accordingly to Table 3 for GMAW with ER70S-6 1.2 mm wire and Ar + 25 % CO_2.

The final acquired signals for the three sensors are shown in Figures 7, *a*–*c*, respectively for optic infrared receiver, magnetic-contact sensor and three-axis accelerometer sensors. These images show the synchronization between the program selection (P2 or P4) according to Table 3, with immediate response shown in current curves. Therefore, it is possible to state that Conparte system was capable for performing waveform synchronized weaving.

The fourth system is a sound monitoring system. The sound monitoring has been always treated as a possibility for welding control but with little application, justified by its low robustness by external noises interference. Sound monitoring is not new (Arata et al., 1979), but successful application has been possible by using modern instrumentation and processing (Cudina et al., 2008 and Cayo and Alfaro, 2009). Differently from these authors, instead of using the signal to identify a trend on its own, here it is propose to use the sound to calculate a regularity index, already established during the monitoring of electrical signals (voltage and current).

Table 3. Programs used for validating Conparte system

Sensor	Program	Current, A	Wire feed speed, m/min
Optic infrared receiver	P2	150	3.0
	P4	200	3.5
Magnetic-contact sensor	P2	300	6.0
	P4	260	8.0
Three-axis accelerometer	P1	220	6.0
	P2	260	8.0

Note. In all cases, the pulse period was set as 18 ms for each program.

The study of metal transfer regularity in short-circuit welding processes has already been done by electrical signals monitoring. Different indexes for establishing suitable conditions, such as regularity in this transfer, have been proposed. One of them is so called Vilarinho's Regularity Index (IVcc), which is a methodology created by the group Laprosolda/UFU based on Equation 2.

$$\mathrm{IVcc} = \frac{\sigma t_{cc}}{t_{cc}} + \frac{\sigma t_{ab}}{t_{ab}}, \tag{2}$$

where σt_{cc} is the standard deviation of short-circuit period (time); σt_{ab} is the standard deviation of open-arc period (time); t_{cc} is the average of the short-circuit period (time); t_{ab} is the average of open-arc period (time).

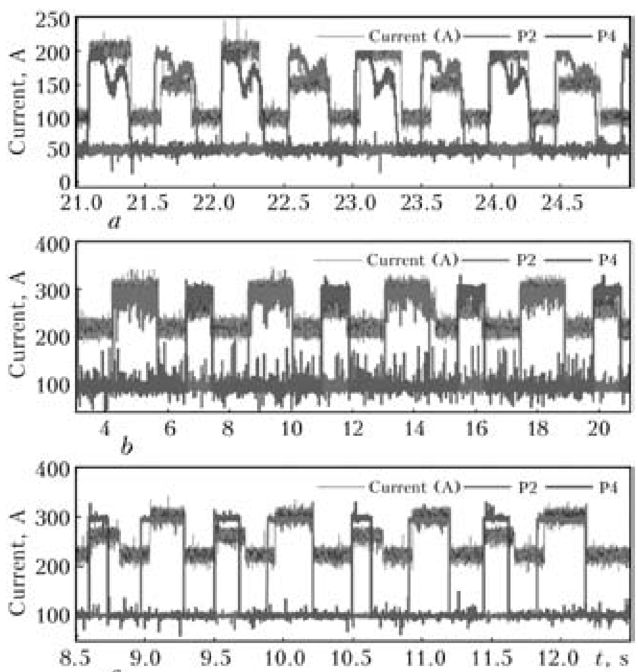

Figure 7. Signals obtained from Conparte system for different sensors: *a* — optic infrared receiver; *b* — magnetic-contact sensor; *c* — three-axis accelerometer

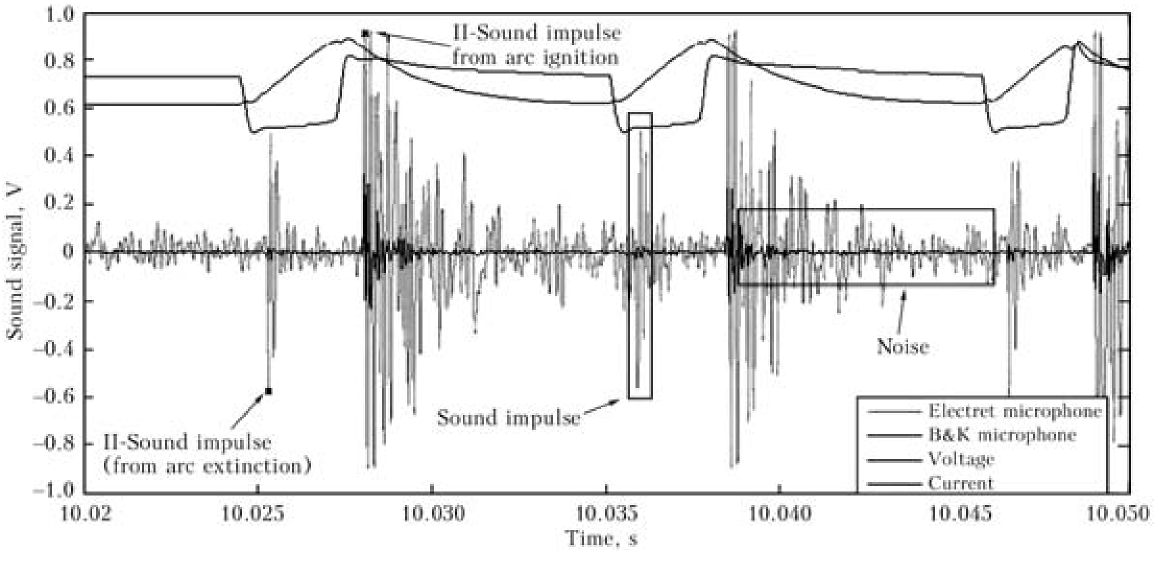

Figure 8. Relationship among current, voltage and sound signals

Therefore, it is presented the use of sound signal from conventional short-circuit GMAW process for IVcc determination and compare it with the one obtained by electrical signals. The use of conventional short-circuit is justified by the fact that besides it has been widely used, it is expected to its use in opposition to derivative processes, which demand high-cost equipment. The final goal is to verify the feasibility of sound monitoring to measure metal transfer regularity without electrical instrumentation or where sound monitoring is simpler and straightforward. Weldments were carried out and comparisons between the results provided by electrical and sound analysis have been carried out. Two types of microphones (electret and commercial ones) and three distances (200, 400 and 800 mm) from the process were employed.

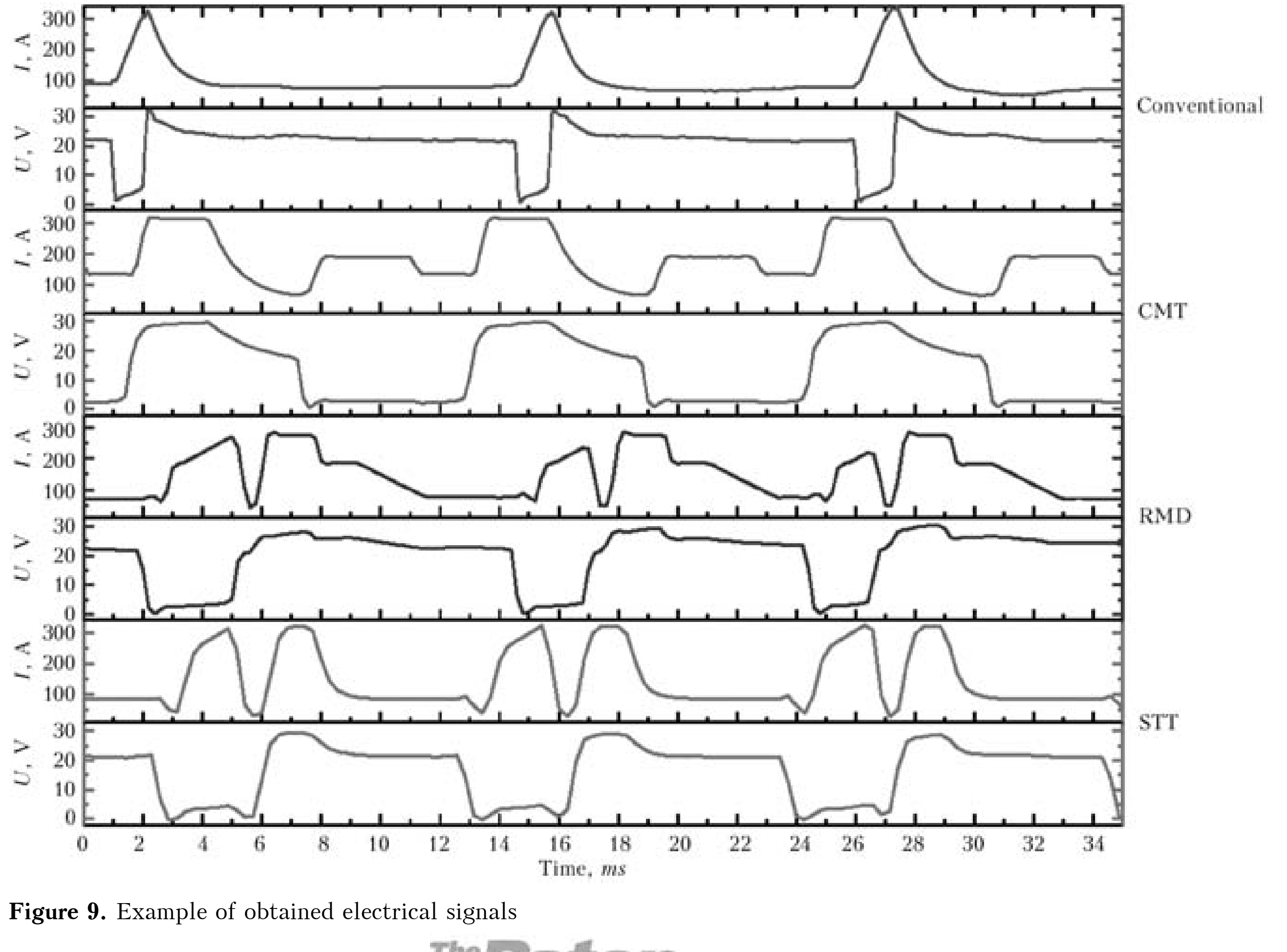

Figure 9. Example of obtained electrical signals

Figure 8 illustrates the obtained results when comparing electrical and sound signals, which after processing calculate the mentioned index with difference lower than 0.5 %. It is possible to conclude that the developed sound monitoring methodology is capable of measuring the regularity index similarly to the one calculated from electrical signals and the suitable distances between the microphones and the welding is from 200 to 400 mm, with a delay time of 0.7 and 1.1 ms, respectively. For 800 mm (2.1 ms delay) the signal-to-noise relationship is so low that calculation was not possible.

Pipe welding with conventional and derivative GMAW. Brazil's continental size and the increasing demand for oil and gas in new industrial areas outside Brazilian south-southeast axis have established a great challenge for fast and reliable expansion of pipelines. Such need requires the continuum development of joining technologies, which main trend has been the development of power sources capable of waveform control. This feature introduced the concept of GMAW derivative process and its version for short-circuit metal transfer (also known as controlled short-circuit) has become a trend in the search for high productivity and high quality weld beads, especially for pipe welding.

It is believed that the waveform control, achieved in such GMAW derivative processes, improves the metal transfer and reaches stability on both process and weld pool. Also the waveform control aggregates value to the power source, i.e., the conventional short-circuit GMAW process requires power sources with lower cost in comparison to the derivative ones. Therefore, it is presented the use of GMAW processes with conventional short-circuit transfer and derivatives (STT, RMD and CMT) for pipe welding, especially for the root pass in pipe welding, which is critical for the cadency of field welding.

The root pass was investigated using downhill progression, 1.2 mm ER70S-6 wire and both Ar + 25 % CO_2 and pure CO_2 as shielding gases. A V-butt joint was used with 15° bevel angle, 1 mm root face and 3 to 4 mm root opening preparation in 8-mm thickness on API 5L X-65 with 8″ pipe. Contact tip to work distance was 15 mm. Conventional short-circuit GMAW and RMD processes were carried out by using PipePro 450 RFC power source. PowerWave 450 power source were used for the STT process, whereas TPS 5000 were employed for CMT. The parameter set for each process was varied together with weaving technique and wire-feed speed, keeping the same amount of deposited material. Analyses of the

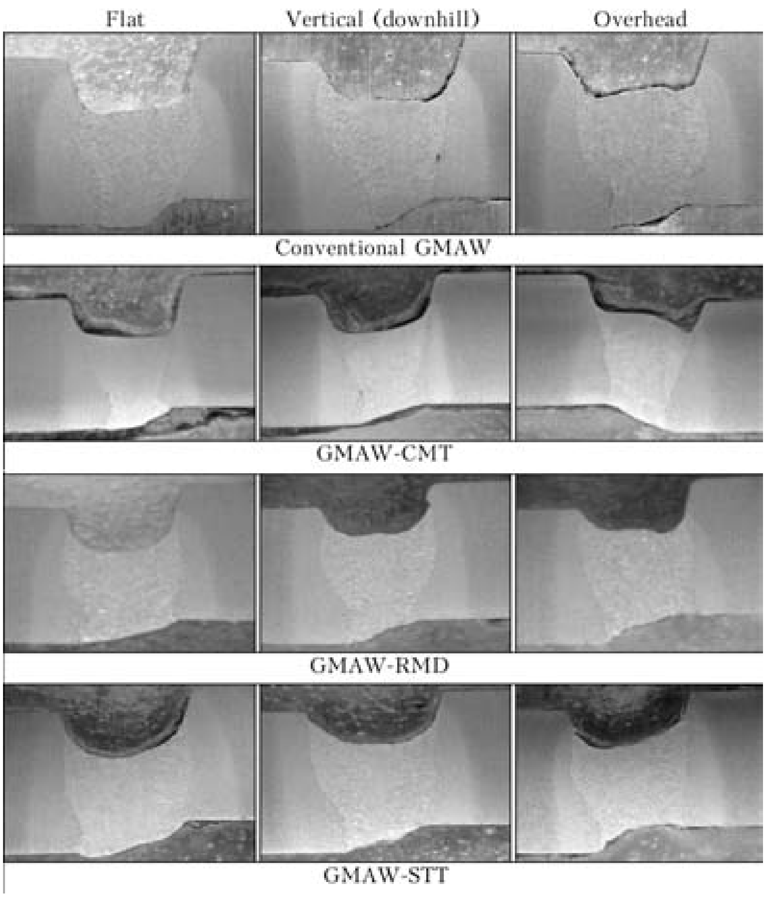

Figure 10. Examples of suitable weld beads (macrographs) obtained with up to 1.5 mm of Hi/Low (thickness 8 mm)

weld beads were carried out by visual inspection and metallographic analysis based on of API 1104 (2010).

Figure 9 presents an example of electrical signals (voltage and current) obtained during welding. The waveforms for the derivative process comprise two stages. The first one refers to the moment when the droplet and the electrode touch the weld pool and there is a control for reducing the increase in welding current. And a second one, when the current increase promoting the droplet detachment, followed by a maintenance of constant value for both voltage and current, which characterizes the open arc phase.

Concerning the bead quality, Figure 10 presents the macrographs with misalignments (Hi/Low) for each process at three positions: flat, vertical (downhill) and overhead. These results show that derivative and conventional short-circuit GMAW processes are capable of achieving sound welds even if misalignments are present. In this case, the correct setup of welding parameter is capable of handling up to 1.5 mm of misalignment in the root (Hi/Low). It indicates that derivative and conventional short-circuit GMAW processes present suitable operational envelopes for all investigated processes, even when misalignment (Hi/Low) up to 1.5 mm is presented in the root.

Final considerations. Different ongoing activities and prospects related to welding technology within Laprosolda group were presented. They indicate the group philosophy, which is aimed to develop different welding processes in three main areas (or work line): the Fundamentals of Welding, Instrumentation for Arc-welding Processes and Application. It is possible to conclude that the results and the techniques presented here are powerful tools for R&D&I in welding technology.

Acknowledgements. *Authors would like to thank Fapemig, CNPq, Laprosolda/UFU and CTBC/Algar Telecom.*

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Received 23.03.2013

MICRO-WELDING OF ALUMINUM ALLOY BY SUPERPOSITION OF PULSED Nd:YAG LASER AND CONTINUOUS DIODE LASER

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The combination of a pulsed Nd:YAG laser and a continuous diode laser could perform the high-performance micro-welding of aluminum alloy. A pulsed Nd:YAG laser was absorbed effectively from the beginning of laser scanning by pre-heating Nd:YAG laser pulse with the superposition of continuous LD, and wide and deep weld bead could be obtained with better surface integrity. 6 Ref., 2 Tables, 8 Figures.

Keywords: *pulsed Nd:YAG laser, aluminum alloy, micro-welding*

Mobile products such as PDA, Notebook PC and mobile phone have been widely used in the fields of information and communication technology. In the automobile industry, hybrid vehicle and electric vehicle attract customers because of their low energy consumption, and they are expected as the key products of next generation. In order to accomplish highly performance of these products, lightweight and high specific strength materials are required. Aluminum alloys have been widely used to achieve lightweight and miniaturization in these fields, hence high-performance welding has been required. A pulsed Nd:YAG laser of 1064 nm in wavelength has been applied to the micro-welding of aluminum alloy [1]. However, the absorption rate of a Nd:YAG laser by aluminum alloys is only 5 % at room temperature, as shown in Figure 1 [2, 3]. Since the absorbed laser energy is very low, high peak power laser system must be used to achieve sufficient penetration depth and acceptable bead width. High peak power is useful to increase the penetration depth and the bead width, but the excessive heat input leads to the deterioration of surface quality and integrity due to the spatter and the porosity [4].

On the other hand, the aluminum alloy shows the high absorption rate around 810 nm as shown in Figure 1. The wavelength 808 nm of diode laser (hereafter LD) is useful to increase the absorption of laser energy, and its absorption rate is 3 times higher than that of Nd:YAG laser of 1064 nm. In addition, low cost and high power LD is available by the recent development of semiconductor technology, and the high brightness LD is also expected. Therefore, the micro-welding technology of aluminum alloy by the combination of a pulsed Nd:YAG laser and a continuous LD was proposed, and efficient absorption of Nd:YAG laser was expected [5, 6].

However, it is difficult to perform the sufficient deep penetration depth with good surface integrity at the beginning of laser scanning. The higher peak power could become the penetration depth deeper, while the deterioration of surface integrity might be noticed. The deeper penetration depth from the beginning of laser scanning with the better surface integrity is very useful for the industrial application. From the viewpoints mentioned above, the effects of superposed continuous LD on micro-welding of aluminum alloy by a pulsed Nd:YAG laser were investigated, and the pre-pulse method was discussed in order to improve the penetration depth even

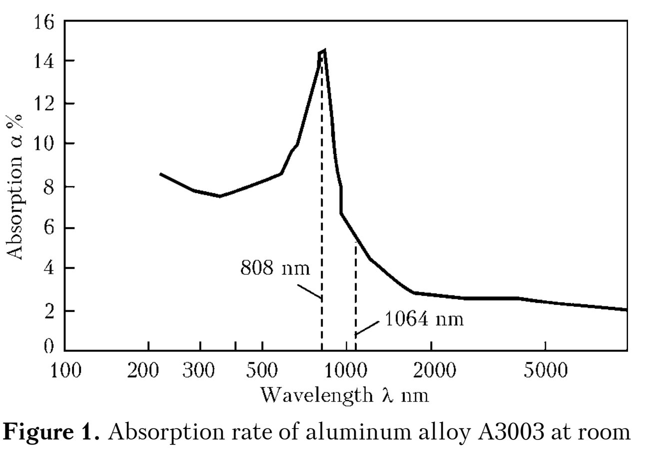


Figure 1. Absorption rate of aluminum alloy A3003 at room temperature

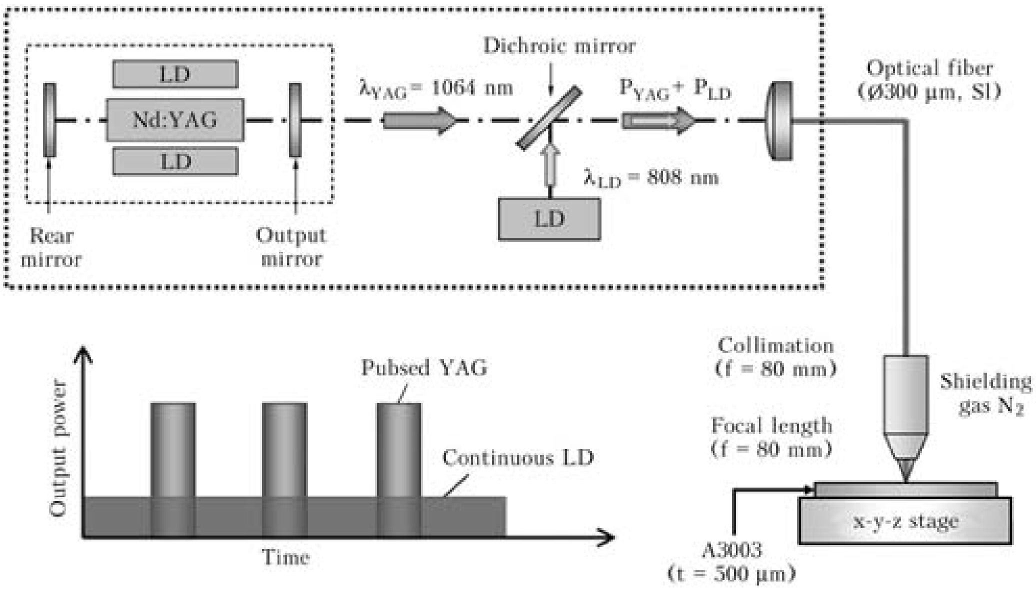
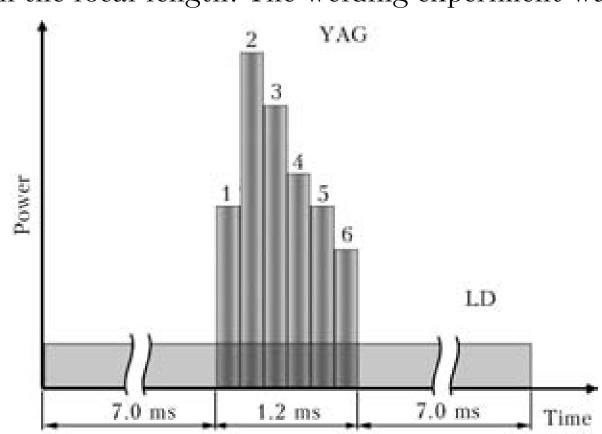


Figure 2. Schematic diagram of laser irradiation system with superposition of pulsed Nd:YAG laser and continuous diode laser

at the beginning of laser scanning by pre-heating Nd:YAG laser pulse.

Experimental procedures. Figure 2 shows the schematic diagram of laser irradiation system. Table 1 shows the specifications of a pulsed Nd:YAG laser and a continuous LD used in this study. A pulsed Nd:YAG laser of 1064 nm in wavelength and continuous LD of 808nm in wavelength were superposed on the same beam axis by a dichroic mirror, and the superposed laser beam of two wavelengths were delivered to a processing head through an optical fiber of 300 μm diameter with SI type. These laser beams were collimated and focused by lenses of 80 mm in the focal length. The welding experiment was carried out by controlling a scanning velocity of stage at the focusing point with N_2 shielding gas of flow rate 57 l/min. The aluminum alloy A3003 of 0.5 mm thickness was used as a specimen except for welding experiments of battery case, and its physical properties are shown in Table 2.

The irradiation waveforms of Nd:YAG laser pulse and continuous LD are shown in Figure 3. The power of pulsed Nd:YAG laser can be controlled every 0.2 ms. In general, the sharp heating up and cooling down might lead to the welding defects such as blow holes and cracks. Therefore, the main pulse of Nd:YAG laser for the processing was controlled with a gradual increment and decrement of laser power during the pulse duration 1.2 ms. In the case of superposition of two laser



Section		P_{YAG}
1	0-0.2 ms	1306
2	9.2 m-0.4 ms	2375
3	0.4 m-0.6 ms	2019
4	0.6 m-0.8 ms	1544
5	0.8 m-1.0 ms	1306
6	1.0 m-1.2 ms	950

Figure 3. Irradiation waveform of pulsed Nd:YAG laser and continuous LD

Table 1. Specifications of pulsed Nd:YAG laser and continuous diode laser

	Nd:YAG laser	Diode laser
Maximum average power P_a	250 W	65 W
Maximum peak power P_p	2.5 kW	–
Wavelength λ	1064 nm	808 nm
Pulse repetition rate R_p	1–500 Hz	CW
Pulse duration τ	0.08–1.2 ms	CW

Table 2. Physical properties of aluminum A3003

Specific heat	900 J/(kg·K)
Thermal conductivity	237 W/(m·K)
Density	2.73 g/cm^2
Poisson's ratio	0.33
Young's modulus	70 kN/mm^2
Coefficient of thermal expansion	2.4·10^{-6} K

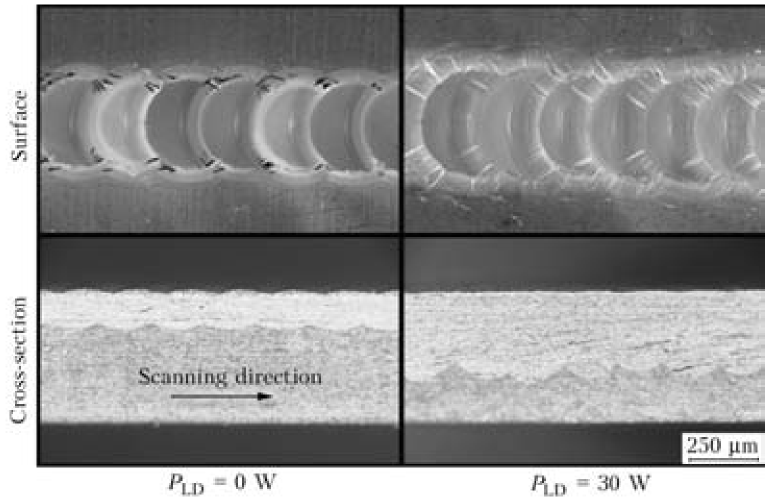


Figure 4. Surface and cross section of weld bead in bead-on-plate irradiation at scanning velocity v = 30 mm/s, pulse duration of Nd:YAG laser τ = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W and average power of LD P_{LD} = 30 W

beams, the irradiation of continuous LD started before the main Nd:YAG pulse as shown in Figure 3.

Effect of superposed continuous diode laser on welding results. Figure 4 shows the surfaces and cross sections of weld bead for aluminum alloy A3003 of 0.5 mm thickness with and without the superposition of continuous LD under the same peak power of Nd:YAG laser. Although the power of continuous LD is approximately 1.2 % against the peak power of pulsed Nd: YAG laser, the superposition of continuous LD made it possible to increase the bead width by 15 % and the weld depth by 150 % compared with welding results without continuous LD. It means that the energy of pulsed Nd:YAG laser could be absorbed effectively to the aluminum alloy by superposition of continuous LD. In general, the absorption rate increases with increasing the temperature of material. Thus, it is considered that the continuous LD could become the surface temperature higher compared with the case without continuous LD [5], hence the high efficient absorption of laser energy made it possible to increase the penetration depth and bead width.

Figure 5 shows the variations of bead width and penetration depth at scanning speed 20 and 35 mm/s in welding experiments of aluminum alloy battery case. The size of battery case is 30 × × 5 × 0.3 mm — width × length × thickness. The top cover plate of 0.5 mm thickness was fitted and pressed into the inside of battery case. The bead width and penetration depth increased with increasing the continuous LD power at both scanning speeds. The penetration depth without continuous LD at scanning velocity 20 mm/s is approximately 500 μm, and the equivalent penetration depth could be obtained even at higher scan-

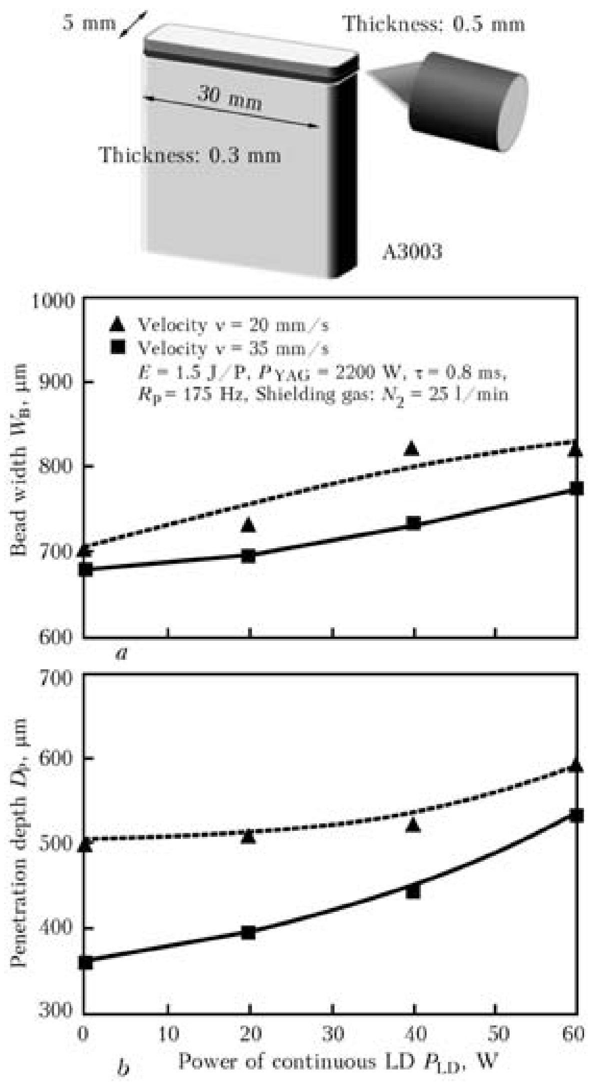


Figure 5. Change of bead width and penetration depth for power of continuous diode laser at scanning velocity ν = 20 and 35 mm/s, pulse duration of Nd:YAG laser τ_p = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W

ning velocity 35 mm/s by the superposition of continuous LD 50 W. When the average power of continuous LD is 60 W, the penetration depth was approximately 1.5 times larger than that without continuous LD. The bead width at scanning velocity 35 mm/s with continuous LD was also higher than that at scanning velocity 20 mm/s without continuous LD. Moreover, good quality weld beads could be obtained as shown in Figure 3.

It is confirmed that the effect of continuous LD on the penetration depth was remarkable at the faster processing speed. The high throughput and quality micro-welding by using pulsed Nd:YAG laser could be expected by superposition of continuous LD.

Effect of pre-Nd:YAG laser pulse on penetration depth at the beginning of scanning. In order to achieve the high absorption of Nd:YAG laser even at the beginning of laser scanning, pre-heating Nd:YAG laser pulse was investigated in the bead-on-plate experiment as shown in Figure 6. It was expected to keep the high surface temperature before the irradiation of main Nd:YAG laser pulse with the irradiation of continuous LD. As shown in Figure 6, *a*, firstly, a continuous LD was irradiated on the specimen surface. Secondly, the pre-Nd:YAG laser pulse was irradiated as a rectangular pulse waveform to increase the surface temperature at the beginning of laser scanning. After the pre-Nd:YAG laser pulse, the main Nd:YAG laser pulses were irradiated.

Since the surface condition has greatly influence on the absorption state, the peak power of pre-Nd:YAG laser pulse on the surface condition was investigated. Figure 6, *b* shows microphotographs of irradiated surface for various peak powers by the single laser shot. For more than peak power 500 W, the specimen surface was molten and became glossy, and the glossiness of specimen surface might reflect a main Nd:YAG laser pulse. On the other hand, the specimen surface was not glossy in the case of peak power 400 W, even the surface temperature increased. Therefore, the peak power 400 W was used for the pre-Nd:YAG laser pulse at pulse width 1.2 ms for 300 μm spot diameter.

Figure 7 shows the surfaces and cross sections of weld bead at the beginning of laser scanning. Here, the power density of pulsed Nd:YAG laser was set in the transitional region between heat conduction welding and key-hole welding. In the case of only main Nd: YAG laser pulse without the pre-Nd:YAG laser pulse, the penetration depth gradually increased in the scanning direction regardless of superposition of continuous LD (B, D). The penetration depth was unstable in the case of pre-Nd:YAG laser pulse without the superposition of continuous LD (A). It is considered that the absorption rate of pulsed Nd:YAG laser was unstable at low specimen sur-

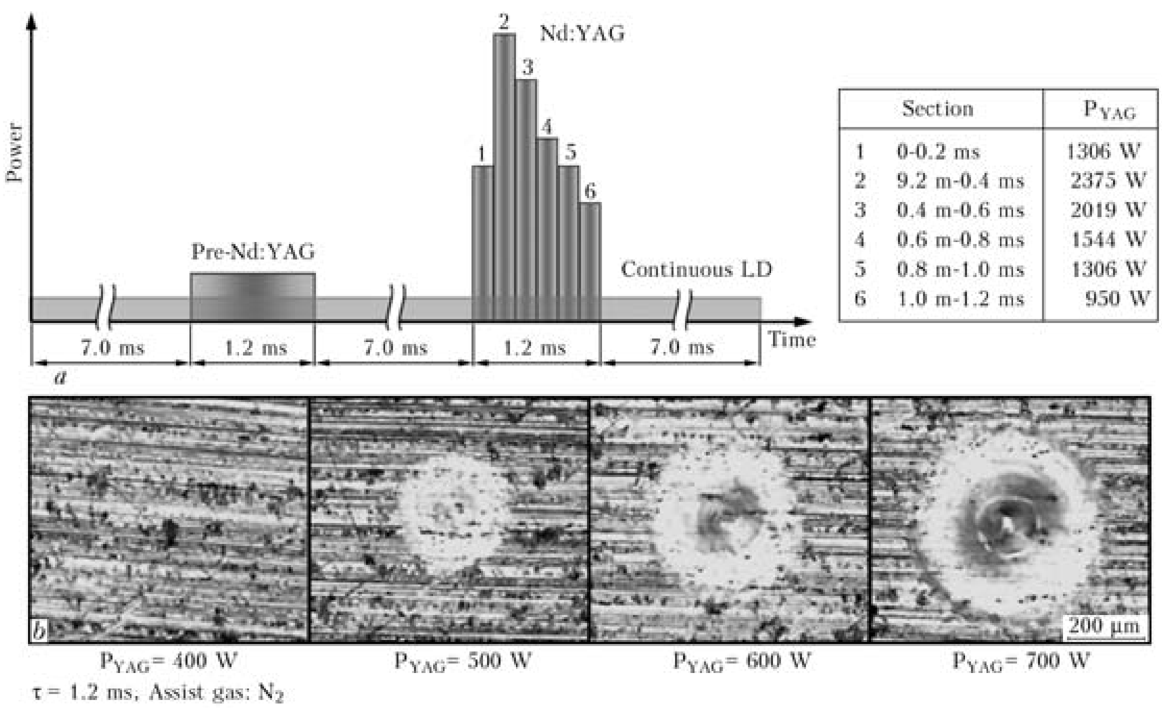


Figure 6. Irradiation waveform and irradiated surface state at pulse duration of Nd:YAG laser τ = 1.2 ms without continuous LD in pre-heating method: *a* — irradiation waveform of pre-heating and main Nd:YAG lase pulse; *b* — irradiated surface for various peak powers of pre-heating pulse by single shot

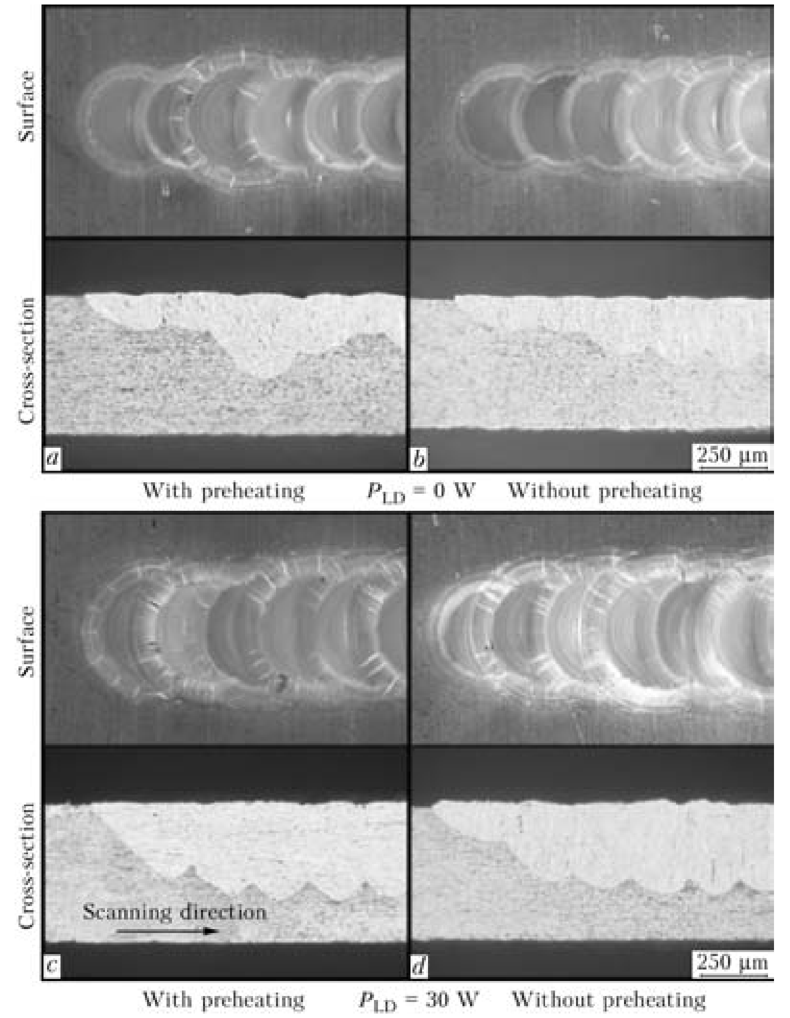


Figure 7. Welding results at the beginning of laser scanning with and without pre-Nd:YAG laser pulse at scanning velocity v = 30 mm/s, pulse duration of Nd:YAG laser τ = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W, peak power of pre-Nd:YAG laser pulse P_{pre} = 400 W and average power of LD P_{LD} = 0, 30 W

face temperature, since the power density is the transition condition between the heat conduction welding and the key-hole welding. On the other hand, in the case of pre-Nd:YAG laser pulse with the superposition of continuous LD (C), it was obvious that the penetration depth became larger from the beginning of laser scanning by stable higher absorption of laser energy. Moreover, the stable welding process could be performed with steady bead width and penetration depth. It indicated that not only the use of pre-Nd:YAG laser pulse but also the combination of pre-Nd:YAG laser pulse and the superposition of continuous LD made it possible to increase the molten volume at the beginning of laser scanning.

The temperature change of specimen surface was investigated by the numerical calculation in order to discuss the welding phenomenon with and without the pre-heating pulse. The general finite element program «ANSYS Rev.11.0», in which the unsteady calculation is possible, was used for the numerical analysis by using the analytical model as shown in Figure 8, *a*. In the case of superposition of continuous LD, the key-hole effect was assumed. Internal heat generation by the heating element of shape mixed column and hemisphere was considered as a heat source as shown in Figure 8, *b*. The total power of a pulsed Nd:YAG laser and a continuous LD was irradiated as an internal heat generation. A continuous LD was irradiated on the specimen surface except for pulsed Nd:YAG laser shot. The absorption rate of pulsed Nd:YAG laser was defined as 15 % for a heat flux and 30 % for an internal heat generation, and 30 W continuous LD was given by temperature dependent absorption rate, which were determined by the former investigation [5, 6]. The pulse waveform of main Nd:YAG laser was the same as shown Figure 6, *a*. Pre-Nd:YAG laser pulse and a main Nd:YAG laser pulse without the superposition of continuous LD were given as a heat flux of absorption rate 15 % as shown in Figure 8, *c*. A pulse of Nd:YAG laser of 300 μm spot diameter was irradiated at the

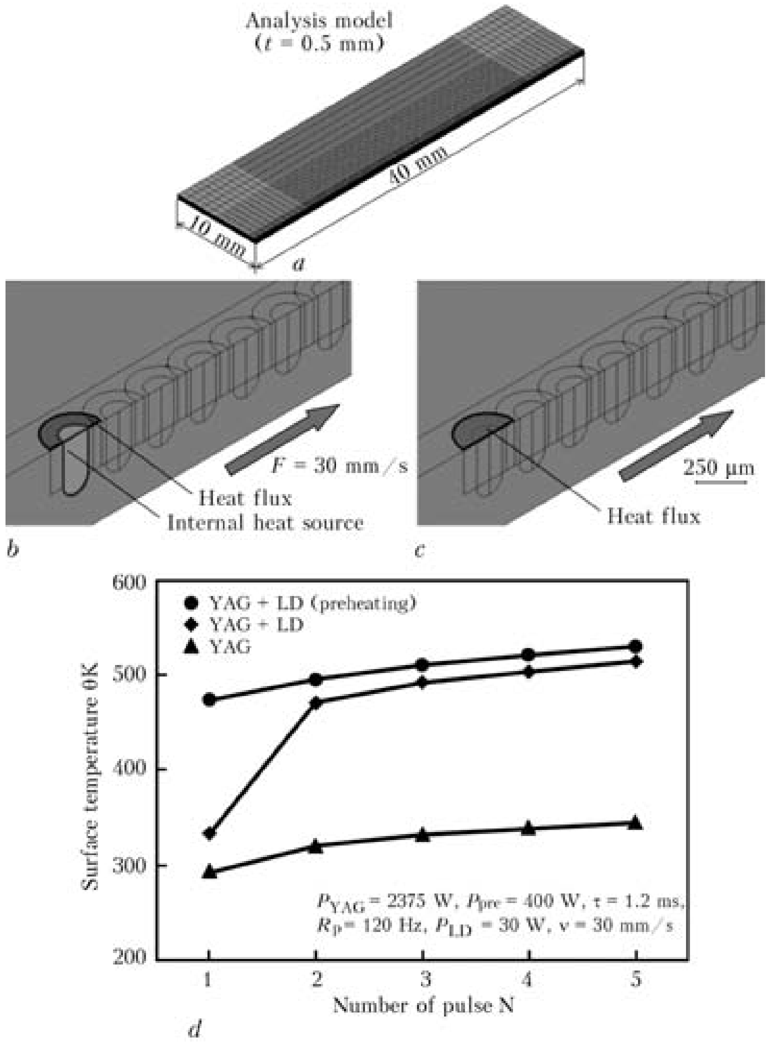


Figure 8. Analytical model and calculated surface temperatures of spot center before irradiation of main Nd:YAG laser pulse with and without pre-Nd:YAG laser pulse at scanning velocity v = 30 mm/s, pulse duration of Nd:YAG laser τ = = 1.2 ms, pulse repetition rate of Nd:YAG laser R_p = 120 Hz, peak power of Nd:YAG laser P_{YAG} = 2375 W, peak power of pre-Nd:YAG laser pulse P_{pre} = 400 W and average power of LD P_{LD} = 0, 30 W: a — whole analytical model; b — analytical model with continuous LD; c — analytical model without continuous LD; d — calculated surface temperatures of spot center before irradiation of main Nd:YAG laser pulse

pulse repetition rate 120 Hz and the scanning speed 30 mm/s. The convective heat transfer condition of air was considered after the set time of laser irradiation. Except for the laser beam irradiated area, the convective heat transfer condition of air was also considered. The pure aluminum thermo physical properties of specimen were used for this analysis. Coefficient of heat transfer and the initial temperature were 35 W/(m^2·K) and 296K, respectively.

Figure 8, d shows the calculated surface temperature of spot center before the irradiation of main Nd:YAG laser pulse. In the case of only Nd:YAG laser pulse, the surface temperature was the same as an initial temperature before the first main Nd:YAG laser pulse, since there was no energy input. Only continuous LD irradiation increased the surface temperature by 40 K. By using both pre-heating pulse and continuous LD, the surface temperature increased approximately 200 K higher than that of main Nd:YAG laser pulse without pre-heating pulse. The absorption rate of Nd:YAG laser to aluminum alloy increases drastically more than 900 K, melting point of aluminum alloy. Without pre-heating pulse and continuous LD, a pulsed Nd:YAG laser was irradiated on the specimen surface at low temperature firstly, which led to the unstable absorption of a pulsed Nd:YAG laser beam. On the other hand, it is easy to reach the melting point in the case with pre-heating pulse and continuous LD compared with the case of only Nd:YAG laser irradiation. Therefore, it was considered that the energy of pulsed Nd:YAG laser could be absorbed effectively and stably to the specimen surface because of its higher surface temperature even at the beginning of laser scanning with pre-heating pulse and continuous LD.

Conclusions

The effects of superposed continuous LD on micro-welding of aluminum alloy by a pulsed Nd:YAG laser were investigated, and the pre-pulse method was also discussed in order to improve the penetration depth even at the beginning of laser scanning by pre-heating Nd:YAG laser pulse. Main conclusions obtained in this study are as follows.

• The energy of pulsed Nd:YAG laser could be absorbed to the aluminum alloy effectively, since the surface temperature of specimen was kept higher by the superposition of continuous LD during the interval time of Nd:YAG laser pulse.

• The high-efficiency and high-quality welding for aluminum battery case could be performed by the superposition of pulsed Nd:YAG laser and continuous diode laser. 1 5% increase in bead width and 150 % increase in penetration depth were obtained by the superposition of continuous LD.

• A pulsed Nd:YAG laser was absorbed effectively from the beginning of laser scanning by pre-heating Nd:YAG laser pulse with the superposition of continuous LD due to the high surface temperature of specimen. The combination of pre-heating Nd:YAG laser pulse and continuous LD made it possible to perform the stable welding state from the beginning of laser scanning by stable absorption of pulsed Nd:YAG laser.

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Received 01.03.2013

MECHANICAL BEHAVIOR AND FAILURE OF SANDWICH STRUCTURES

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The failure behavior of composite sandwich beams under three- and four-point bending was studied. The beams were made of unidirectional carbon/epoxy facings and various core materials including PVC closed-cell foams, a polyurethane foam and an aluminum honeycomb. Various failure modes including facing wrinkling, indentation failure and core failure were observed and compared with analytical predictions. It was established that the initiation, propagation and interaction of failure modes depend on the type of loading, constituent material properties and geometrical dimensions. 11 Ref., 2 Tables, 4 Figures.

Keywords: *investigation of failure behavior, three-point bending, sandwich beams, carbon-epoxy facing, various core materials, strength-to-weight ratio*

Sandwich structures consisting of strong and stiff facings and light weight cores offer improved stiffness and strength to weight ratios compared to monolithic materials. Under flexural loading the facings carry almost all of the bending, while the core takes the shear loading and helps to stabilize the facings. Facing materials include metals and fiber reinforced composites. The latter are being used in advanced applications due to the large strength-to-weight ratio. The core materials mainly include honeycombs, foams and wood.

Possible failure modes of sandwich structures include tensile or compressive failure of the facings, debonding at the core/facing interface, indentation failure under concentrated loads, shear core failure, wrinkling of the compression face and global buckling. Recently, the authors have performed a thorough investigation of the failure behavior of sandwich beams with facings made of carbon/epoxy composite material and core made of foam materials [1–6].

In the present work, failure modes were investigated experimentally in sandwich beams under four-point and three-point bending. Failure modes observed and studied include core failure, face sheet wrinkling and indentation failure.

Materials and specimens. The sandwich beams were fabricated from 8-ply unidirectional carbon/epoxy (AS4/3501-6) facings and various core materials. The facings were bonded to the core with an epoxy adhesive (Hysol EA 9430). The assembly was cured at room temperature. The facings and core had a thickness of 1

Table 1. Properties of balsa wood, aluminum and foam-filled honeycomb, and polyurethane materials

Property	Balsa Wood CK57	Aluminum Honeycomb PAMG 5052	Foam Filled Honeycomb Style 20	Polyurethane FR-3708
Density, ρ, kg/m^3 (lb/ft^3)	150 (9.4)	130 (8.1)	128.3 (8)	128.3 (8)
In-plane long. comp. elast. mod., E_{1c}, MPa (ksi)	129.5 (18.8)	9.5 (1.38)	24.1 (3.5)	38.5 (5.6)
In-plane long. tens. elast. mod., E_{1t}, MPa (ksi)	93.6 (13.6)	4.5 (0.65)	1.3 (0.19)	416.6 (60.4)
In-plane trans. comp. elast. mod., E_{2c}, MPa (ksi)	129.5 (18.7)	6 (0.87)	7.6 (1.1)	38.5 (5.6)
Out of plane comp. elast. mod., E_{3c}, MPa (ksi)	5394 (782.3)	2125 (308)	269.1 (39)	108.7 (15.8)
Transverse shear elast. mod., G_{13}, MPa (ksi)	58.7 (8.5)	579 (84)	8.5 (1.23)	10.3 (1.49)
In-plane long. comp. strength, F_{1c}, MPa (ksi)	0.78 (0.11)	0.2 (0.03)	0.4 (0.06)	1.15 (0.17)
In-plane long. tensile strength, F_{1t}, MPa (ksi)	1.13 (0.16)	1.63 (0.24)	0.48 (0.07)	1.1 (0.16)
In-plane trans. comp. strength, F_{2c}, MPa (ksi)	0.78 (0.11)	0.17 (0.03)	0.32 (0.05)	1.15 (0.17)
Out of plane comp. strength, F_{3c}, MPa (ksi)	9.6 (1.39)	11.8 (1.7)	1.35 (0.2)	1.74 (0.25)
Transverse shear strength, F_{13}, MPa (ksi)	3.75 (0.54)	3.45 (0.5)	0.75 (0.11)	1.4 (0.2)

Table 2. Properties of carbon/epoxy facings, adhesive, and H100 and H250 PVC foams

	Facing	FM-73 adhesive	Foam Core (H100)	Foam Core (H250)
Density, ρ, kg/m^3	1.620	1.180	100	250
Thickness, h, mm	1.01	0.05	25.4	25.4
Longitudinal modulus, E_1, MPa	147.000	1.700	120	228
Transverse modulus, E_3, MPa	10.350		139	403
Transverse shear modulus, G_{13}, MPa	7.600	110	48	117
Longitudinalcompressive strength, F_{1c}, MPa	1.930		1.7	4.5
Transverse compressive strength, F_{3c}, MPa	240		1.9	6.3
Transverse shear strength, F_{13}, MPa	71	33	1.6	5.0

and 25.4 mm, respectively. Beam specimens 25.4 mm wide and of various lengths were cut from the sandwich plates. Tables 1 and 2 give some characteristic properties of the sandwich constituent materials.

Experimental procedure. Special test fixtures were fabricated to provide three- and four-point bending for beams of various lengths. Five span lengths of 10.2, 20.3, 25.4, 40.6 and 76.2 cm were tested. In studying the effects of pure bending, special reinforcement was provided for the core at the outer sections of the beam to prevent premature core failures. Also, under three-point bending, the faces directly under concentrated loads were reinforced with additional layers of carbon/epoxy to suppress and prevent indentation failure. Only in the case when the indentation failure mode was studied, there was no face reinforcement. The concentrated load was applied to the specimens with a cylinder of diameter of 25.4 mm (1 in.).

Strains on the outer and inner (interface between facing and core) surfaces of the facings were recorded with strain gages. Most gages were oriented along the axis of the beam, but some were mounted in the transverse direction to record transverse strains. Beam deflections were measured with a displacement transducer (LVDT) and by monitoring the crosshead motion. The deflection was also monitored with a course moire grating (31 lines/cm). Longitudinal and transverse strains in the core were measured with finer moire gratings of 118 and 200 lines/cm. The deformation of the core was also monitored with birefringent coatings using reflection photoelasticity.

Failure modes. A number of failure modes were recorded and studied in the composite sandwich beams subjected to three- and four-point bending. They include wrinkling of the compression facing, core failure and indentation of the loaded face. These failure modes are discussed in the following sections.

Compression facing wrinkling. Compression facing wrinkling failures were observed in sandwich beams under both four-point and three-point bending. Figure 1 shows moment versus strain results for two different tests of sandwich beams with Divinycell H100 cores under four-point bending. Evidence of wrinkling is shown by the sharp change in recorded strain on the compression facing, indicating inward and outward wrinkling in the two tests. In both cases the critical wrinkling stress was $\sigma_{cr} = 673$ MPa.

Wrinkling is a localized short-wave buckling of the compression facing. Wrinkling may be viewed as buckling of the compression facing supported by an elastic continuum, the core. The critical wrinkling stress according to Heath [7] is given by

$$\sigma_{cr} = \left[\frac{2}{3}\,\frac{h_f}{h_c}\,\frac{E_{c3}E_{f1}}{(1-\nu_{12}\nu_{21})}\right]^{12}, \qquad (1)$$

where h_f, h_c — facing and core thicknesses, respectively; E_{f1}, E_{c3} — facing and core moduli, respectively; ν_{ij} — Poisson's ratio associated with loading in the i-direction and strain in the j-directio; and the indices 1 and 3 refer to the in-plane and through-the-thickness directions, respectively.

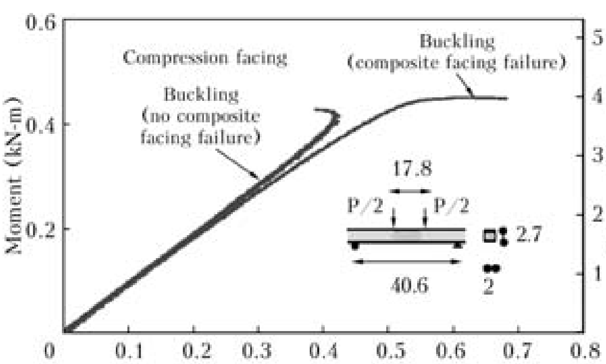

Figure 1. Facing wrinkling in sandwich beam under four-point bending (Divinycell H100 foam core; dimensions are in cm)

Equation (1) predicts the following value of the wrinkling stress σ_{cr} = 687 MPa.

This value is close to the experimental value of 673 MPa.

In the case when shear is present in addition to bending, the influence of the transverse shear modulus of the core, G_{c13}, must be taken into account. An expression given by Hoff and Mautner [8] has the form

$$\sigma_{cr} = c(E_{f1}E_{c3}G_{c13})^{1/3}, \qquad (2)$$

where c is a constant usually taken as equal to 0.5, 0.6, or 0.65. Note that the critical stress in this expression depends only on the elastic moduli of the facing and core materials. In the relation above the core moduli are the initial elastic moduli if wrinkling occurs while the core is still in the linear elastic range. This requires that the shear force at the time of wrinkling be low enough or, at least,

$$V < A_c F_{cs}, \qquad (3)$$

where A_c is core cross sectional area and F_{cs} the shear strength of the core. This is the case for long span beams under three-point bending.

Core failure. Core failures were observed in sandwich beams under three-point bending. The core carries primarily the applied shear loading. In short beams under three-point bending the core is mainly subjected to shear and failure occurs when the maximum shear stress reaches the critical value (shear strength) of the core material. In long-span beams the normal stresses in the core become of the same order of magnitude or even higher than the shear stresses. In this case, the core is subjected to a biaxial state of stress and fails according to an appropriate failure criterion. It was shown that failure of the core materials can be described by the Tsai-Wu failure criterion [9]. For a beam loaded under combined bending and shear, the foam is subjected to longitudinal normal stress, σ_1, and in-plane shear stress, τ_5 (τ_{13}). The Tsai-Wu criterion for this case takes the form

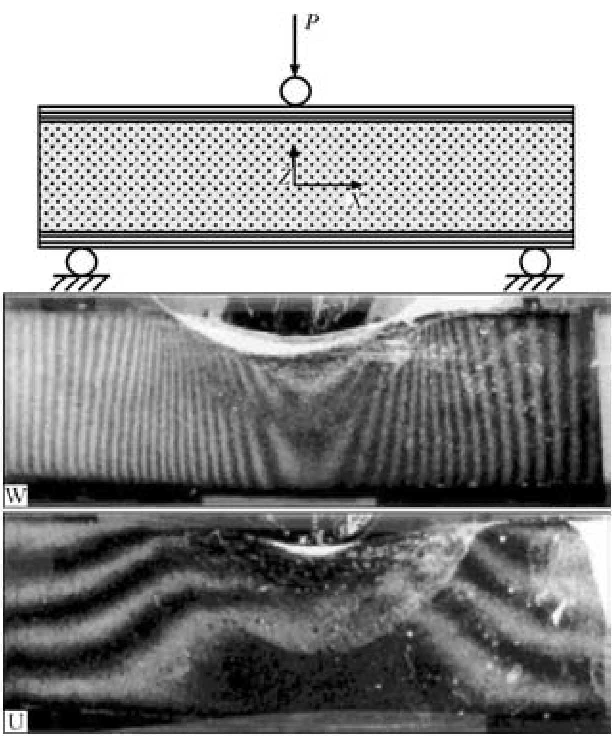

Figure 2. Moire fringe patterns corresponding to horizontal and vertical displacements in sandwich beam under three-point bending (12 lines/mm; Divinycell H250 core)

$$f_1\sigma_1 + f_{11}\sigma_1^2 = 1 - k^2, \qquad (4)$$

where

$$f_1 = \frac{1}{F_{1t}} - \frac{1}{F_{1c}}, \quad f_{11} = \frac{1}{F_{1t}F_{1c}}, \quad f_{55} = \frac{1}{F_5^2}, \quad k = \frac{\tau_5}{F_5},$$

F_{1t}, F_{1c} = tensile and compressive strengths in the in-plane (1, 2) direction. F_5 = shear strength on the 1–3 plane.

In the above equations σ_1, σ_3 and τ_5 are the normal and shear stresses referred to the principal material directions (in-plane is direction 1 and through-the-thickness is direction 3), F_{1c} and F_{1t} are the compressive and tensile strengths along the in-plane direction, F_{3c} and F_{3t} are the compressive and tensile strengths along the through-the-thickness direction and $F_5(= F_{13})$ is the shear strength on the 1–3 plane.

The state of deformation and failure mechanisms in the core were studied by means of moire method. Figure 2 shows moire fringe patterns in the core of a sandwich beam with Divinycell H250 core under three-point bending. The moire fringe patterns corresponding to the horizontal and vertical displacements away from the applied load consist of nearly parallel and equidistant fringes from which it follows that the normal strains are zero, while the shear strain is nearly constant across the core thickness. This is valid only in the linear range.

Indentation failure. Indentation failure was observed in beams under three-point bending when no special reinforcement of the facing or the core was provided in the area under the load. Figure 3 shows the variation of the applied load with the displacement of the indenting roller for a 36 cm long beam under three-point bending. The displacement represents the sum of the global beam deflection and the local indentation, but it is more sensitive to the local indentation. Therefore, the proportional limit of the load-displacement curve is a good indication of initiation of indentation. In the present case the beam was made with a Divinycell H100 core. The load at initiation of indentation is 735 N. The peak load measured was P_{max} = 1080 N.

The indentation failure of the sandwich beam can be predicted by treating the loaded face as a beam resting on a foundation. For linear elastic behavior, the core is modeled as continuous distributed linear tension/compression springs. The stress σ at the interface between core and facing is proportional to the local deflection, w

$$\sigma = kw, \tag{5}$$

where k is the foundation modulus given by [10].

$$k = 0.64\,\frac{E_{c3}}{h_f}\,\sqrt[3]{\frac{E_{c3}}{E_{f1}}}. \tag{6}$$

For a long (assumed infinite) facing the deflection w_P under the load P is [10]

$$w_P = \frac{P\lambda}{2kb}, \tag{7}$$

where

$$\lambda = \frac{1.18}{h_f}\,\sqrt[3]{\frac{E_c}{E_{f1}}} \tag{8}$$

and b is the width of the facing.

Yield of the core under the load occurs when the interfacial stress σ reaches the yield stress of the foam core. The critical load at initiation of core yield is calculated from Eqs. (5) to (8) and the yield condition as

$$P_{cy} = 1.70\sigma_{ys}bh_f\,\sqrt[3]{\frac{E_{f1}}{E_c}}, \tag{9}$$

where σ_{ys} is the yield stress of the core.

As the load increases beyond the yield value, plastic deformation propagates through the core from the center to the ends of the facing. For a rigid-perfectly plastic foundation the local bending stress at the upper surface of the facing is given by [11]

$$\sigma_{ft} = \frac{9P^2}{16b^2h_f^2\sigma_{ys}}. \tag{10}$$

For a beam in three-point bending the global stress in the facing is

$$\sigma_{fb} = \frac{PL}{4bh_f(h_f + h_c)}, \tag{11}$$

where h_c is the thickness of the facing.

Indentation failure occurs when the sum of the local and global bending stresses, σ_{ft} and σ_{fb}, reaches the compressive strength of the facing

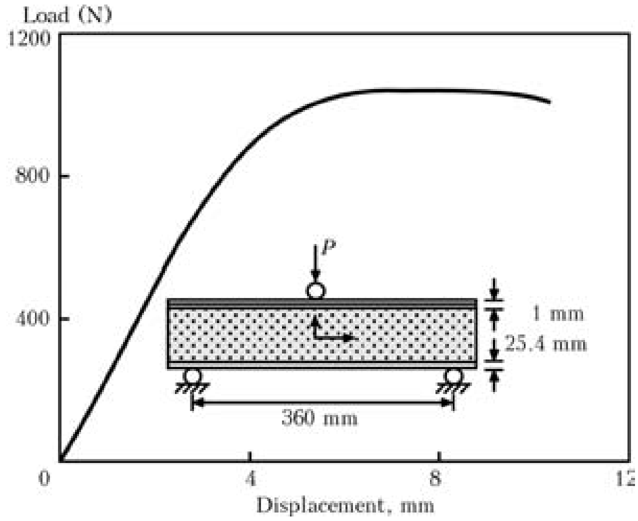

Figure 3. Load versus deflection under load of sandwich beam under three-point bending (carbon/epoxy facings, Divinycell H100 core)

material. The load at initiation of indentation in Figure 3 is 735 N and agrees with the calculated value of 800 N from Eq. (9). The peak load measured is P_{max} = 1080, while the calculated value is P_{max} = 1310 N. The difference in the results may be attributed in the simplifying assumption of a rigid-perfectly plastic foundation.

Failure mode transition. From the above discussion it is obvious that initiation of a particular failure mode depends on the geometrical characteristics, the material properties and the loading conditions of the beam. In the case of beams under three-point bending when reinforcement of the facings or the core is provided to suppress indentation failure, the prevalent failure modes are facing wrinkling and core failure. For short spans, core failure occurs first and then it triggers facing wrinkling. For long spans, facing wrinkling can occur before any core failure. Thus, a curve for the critical load for core failure initiation versus span length is obtained. On the other hand, the critical load for facing wrinkling as a function of span length can be predicted from Eq. (2). Figure 4 shows curves of the critical

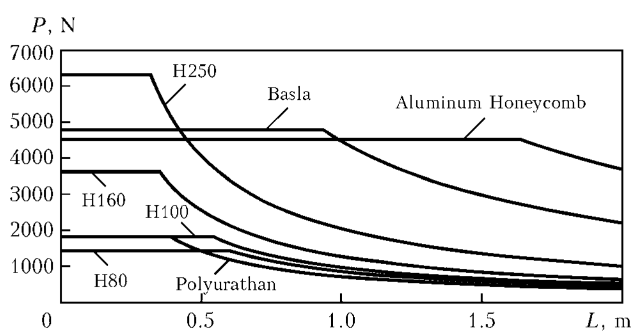

Figure 4. Critical load versus span length for failure initiation in sandwich beams under three-point bending. Horizontal lines indicate core shear failure and curved lines indicate failure by compressive facing wrinkling

load versus span length for initiation of failure by core failure and facing wrinkling for a sandwich beam with various core materials. The intersection of the curves defines the transition from core failure initiation to facing wrinkling initiation. Note that for core materials H250, balsa wood and aluminum honeycomb with increased through-the-thickness Young's modulus the compressive facing wrinkling failure curve is displaced, according to Eq. (2) to the right, and therefore, the critical length for failure mode transition from core failure to wrinkling increases. Thus, as the through-the-thickness Young's modulus of the foam increases, the critical length of the beam for failure mode transition from core failure to wrinkling, also increases.

Conclusions

Failure modes of composite sandwich beams depend on the type of loading, constituent material properties and geometrical dimensions. For sandwich beams made of unidirectional carbon/epoxy facings and PVC closed-cell foam cores failure modes observed and studied include core failure, compressive facing wrinkling and indentation failure. Experimental results were compared with theoretical predictions whenever they were available. Following initiation, interaction of failure modes takes place leading to catastrophic fracture. Thus, failure initiation by plastic deformation of the core degrades the supporting role of the core and precipitates other failure modes, such as facing wrinkling. When core failure and stiffness degradation occur first, the critical wrinkling stress is substantially reduced. Thus, catastrophic failure of a sandwich beam appears to be the result of initiation propagation and interaction of failure modes, as influenced by type of loading, constituent material properties and geometrical dimensions.

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Received 08.04.2013

PLASMA PROCESSES IN METALLURGY AND TECHNOLOGY OF INORGANIC MATERIALS

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Equipment-technological classification of plasma processes in metallurgy and material treatment is stated. It allowed evaluating the prospects of plasma process practical application and ways for structural-technological arrangement optimizing. The equipment for shaft furnaces with plasma heating and processes of plasma effect on metallurgical melts have close prototypes in classical metallurgy. Jet-plasma processes, oriented on receiving of substances in dispersed state, require development of the original equipment. The authors realized the processes of hydrogen-plasma reduction of refractory metal oxides, plasma reduction melting of oxides of iron group and production of metal compounds (carbides, nitrides, oxides, etc.) allowing manufacture of products in a form of dispersed powders. They differ by possibility of energy- and resource saving, receiving of products with specific service properties and environmental compatibility. Proposed is a concept of modular energy-technological complex joining energy generation and chemical-metallurgical production of metals, steels and alloys from natural and technogenic raw materials on plasma method basis. Such pollution-free complex allows reducing energy- and resource consumption. 15 Ref., 10 Figures.

Keywaords: *jet-plasma processes, dispersed powders, plasma-chemical installation, tungsten, energy- and resource saving, energy-technological complex, plasma-arc liquid-phase reduction of iron*

The investigations of physical-chemistry and technology of thermal influence of plasma on the material in different states of aggregation are based on scientific philosophy about effect of highly-concentrated power sources on the material [1, 2]. They are directed on development of pollution-free energy- and resource saving processes for manufacture of the materials with specific properties, including nanomaterials.

A theory of processes of metal reduction in different states of aggregation, including under effect of the thermal plasma flows [3, 4], was developed as a result of systematic investigations of thermodynamics, kinetics and mechanism of reduction of oxide systems using current methods for investigation of topochemical reactions, provisions of heterogenous catalysis and absolute reaction rate theory.

Procedure for the investigation of plasma processes was developed based on high-temperature thermodynamic analysis, mathematical modelling and experimental kinetic investigations using specially designed equipment [5].

A decisive role of heat-and-mass exchange on treated dispersed material distributed in a plasma flow and its transfer in a gas phase, i.e. level of the process homogenization [3, 5–8] was determined during the jet-plasma processes.

Equipment-technological classification of plasma processes in metallurgy and material treatment is stated. It allowed evaluating the prospects of their practical application as well as ways for structural-technological arrangement optimizing [7] (Figure 1). Domestic works in the field of plasma technique application were carried out in a number of organizations, but, unfortunately, did not receive significant development. However, application of the electric arc plasmatrons of megawatt power promotes successful application of plasma in the industrial shaft aggregates (for example, in plasma cupola in USA) or in the processes of plasma treatment of zinc-containing dusts at plant of Steel company (Sweden).

The processes of plasma effect on metallurgical melts, which are structurally arranged in a form of plasma furnaces, obtained sufficiently wide application in number of variants as refining and alloying remelts and plasma heating of metal before continuous casting. The domestic developments realized at Chelyabinsk metallurgical plant were transferred at the plant in Freital (former German Democratic Republic), where around 150 grades of quality steels and alloys were successfully manufactured. Afterwards, they were used in Austria under plant license (50-ton plasma furnace of FEST-Alpine company). We have developed and implemented a process of plasma reduction melting of oxide raw

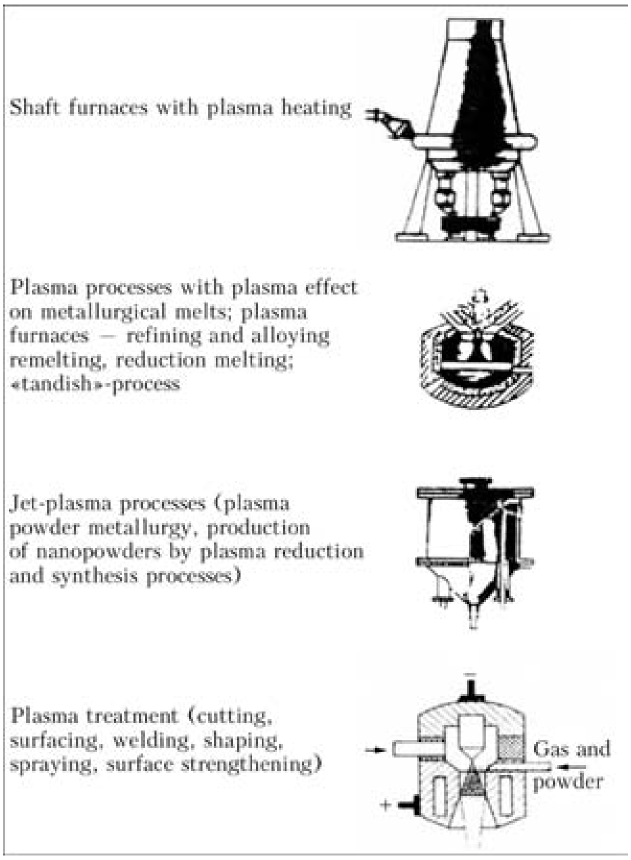

Figure 1. Equipment-technological classification of the plasma processes in metallurgy and material treatment

material, applicable to manufacture of metallic cobalt (Figure 2, 3), afterward used for nickel production, at «Yuzhuralnikel» industrial complex.

Analysis of the fourth class processes is not a subject of this paper, however, their spread in industry should be noted, for example the processes of plasma cutting and spraying. The plasma treatment of surface is highly perspective as well.

In contrast to the processes of the first two classes, where plasma equipment has similar prototypes in the classical metallurgy, development

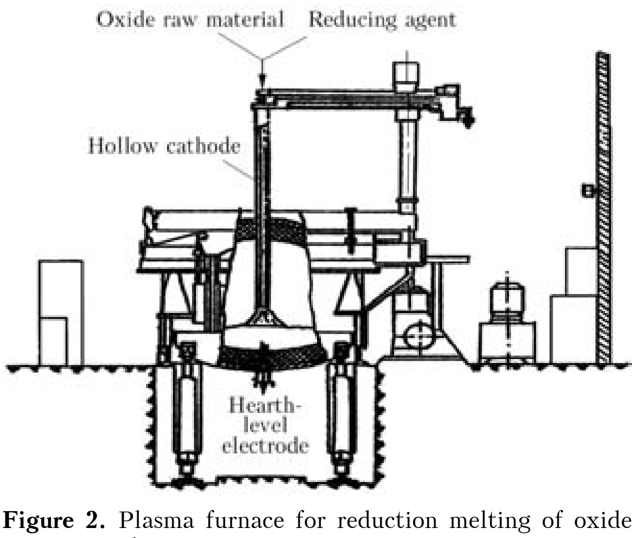

Figure 2. Plasma furnace for reduction melting of oxide raw materials

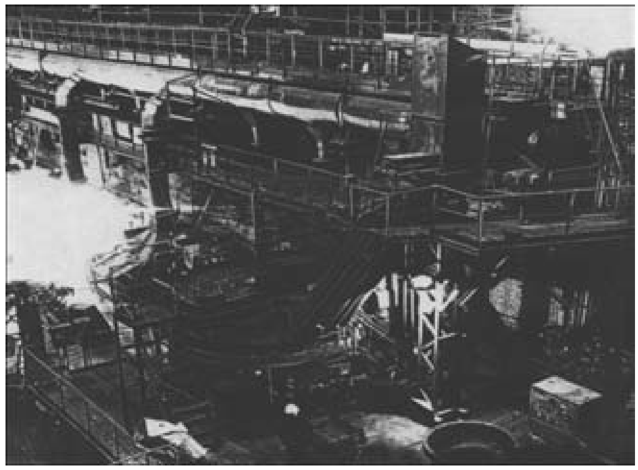

Figure 3. Industrial plasma furnace for reduction melting of oxide raw materials

of the original equipment is required for the third class processes (jet-plasma).

The jet-plasma processes are as a rule oriented on production of materials in dispersed state. The plasma processes of powder production are distinguished by a versatility (Figure 4). Spheroidized, clad powders as well as powders of elements and compounds of different dispersion, including nanosized, were produced with the help of physical and physical-chemical processes during introduction of material in any state of aggregation in the plasma, generated by different sources of various chemical composition.

For the first time in world practice, we have realized an industrial process of hydrogen-plasma reduction of tungsten oxide with production of ultradispersed tungsten powder. The materials with special service properties were received on its basis [9]. It is shown that the plasma metallurgical processes are energy- and resource saving and provide environmental compatibility under condition of rational object choice and optimization of structural-technological arrangement.

Series of practical applications based on peculiarities of ultradispersed state (reduction of temperature and energy consumption at compacting, intensifying of welding and sintering processes, obtaining of hard alloys of increased hardness and wear resistance on their basis) was demonstrated for ultradispersed products of tungsten oxide plasma reduction.

Structure of plasma-chemical installation for production of nanopowders of metals and chemical compounds at interaction of dispersed and vaporous raw material in jet of the thermal plasma generated by electric arc plasmatron (Figure 5) was developed and patented.

A number of plasma-chemical processes of production of metal and compound nanodispersed powders were investigated. Determined are the

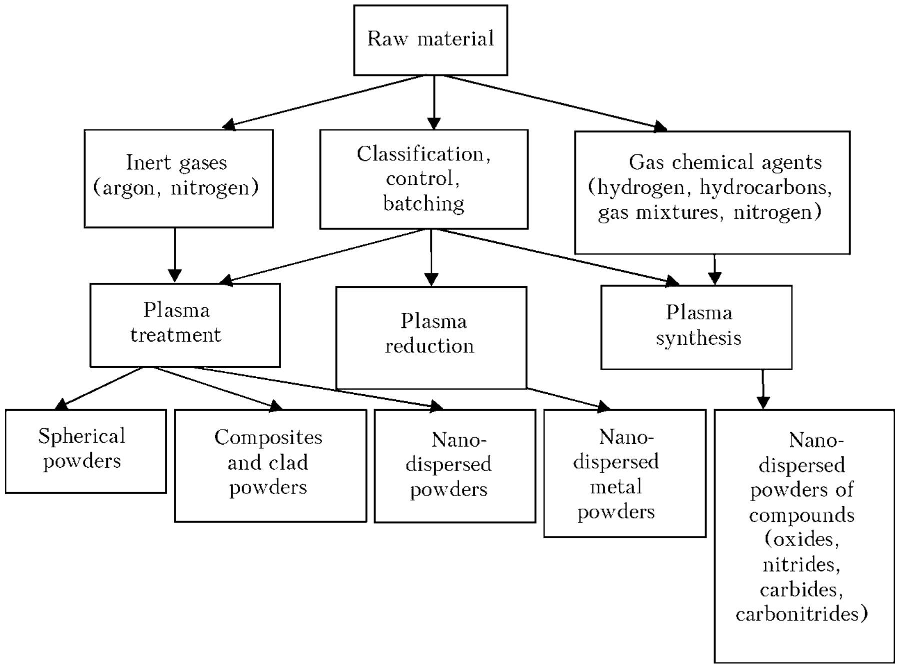

Figure 4. Scheme of plasma powder production technology

thermodynamic and kinetic dependencies and control parameters, providing production of powders of specified chemical and dispersed compositions. The methods were developed for control of average size of produced powder particles during the change of enthalpy of plasma jet, raw material consumption, structural peculiarities of reactor as well as application of gas quenching to the products of plasma-chemical interaction. Advantages of the proposed technology are shown by produced nanopowders (metals, carbides, nitrides, carbonitrides, oxides, etc), short duration of plasma processes (< 0.01 s), high performance of equipment, possibility of application of traditional raw material base without preliminary preparation and significant efficiency range (0.1 ... n·10 kg/h) [10–13].

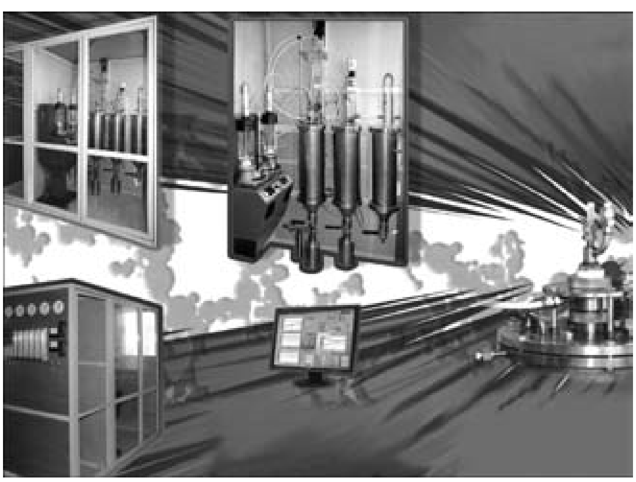

Figure 5. Plasma-chemical installation for nanopowder synthesis

Physical-chemical fundamentals and principles of structural-technological arrangement were developed for a production process based on synthesis of tungsten-carbon system nanopowders (Figure 6) in hydrocarbon plasma. The latter are used for production of tungsten monocarbide nanopowders as a basis for production of nanostructured hard alloys with significantly improved service properties (Figure 7). The urgency of this issue for domestic powder metallurgy is determined by the following factors. Today, Russian industry consumes around 3000 hard alloys (approximately 10 % of the world consumption). One third of this amount is purchased abroad, 1200 t/year are manufactured by KZTS, 300 t

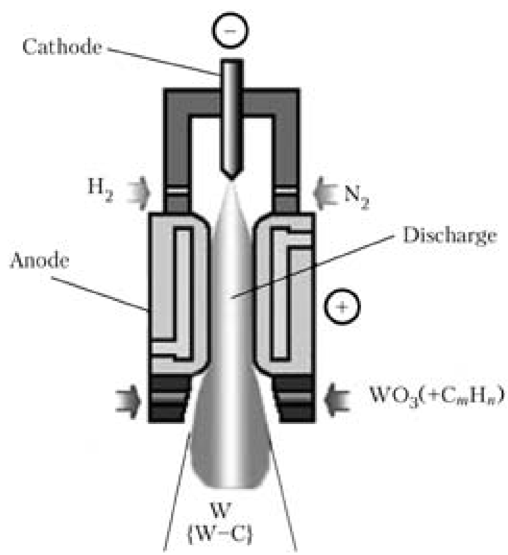

Figure 6. Principle scheme for production of tungsten and {W–C} nanopowders in arc discharge thermal plasma jet

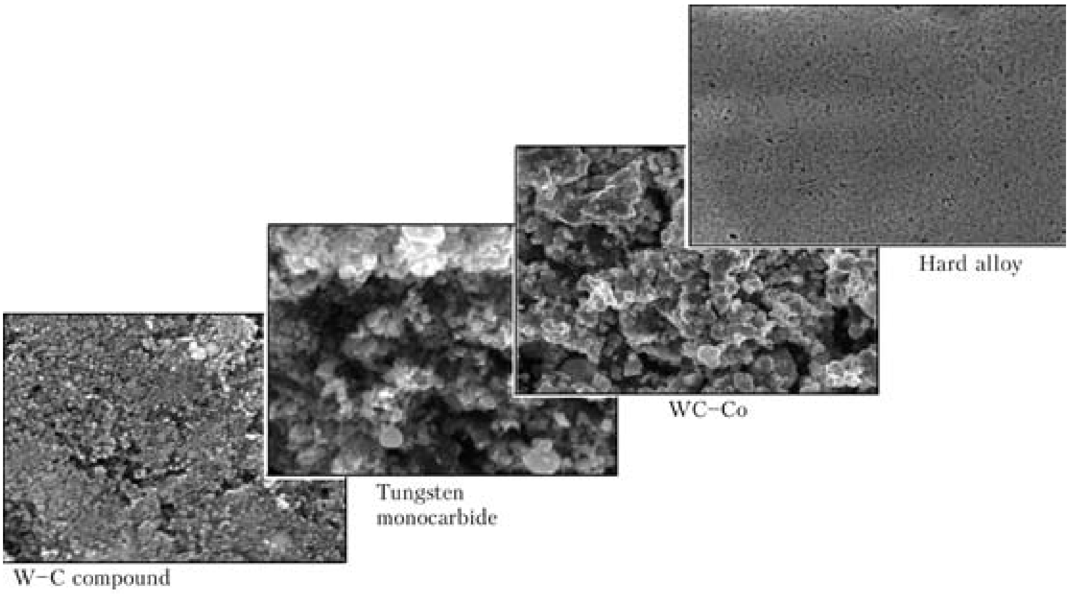

Figure 7. Stages of production of nanostructured hard alloy

are made by «Pobedit» plant, 100 t is from «ALG» company and the rest are produced by other small manufacturers. At present time, the Russian enterprises smelt only average- and coarse grain (more than 1 μm) hard alloys. All over the world, the problem of increase of hard alloy quality is solved by their nanostructuring.

Forms of perspective practical application of nanopowders for development of material with specific properties were studied and partially tested, for example in modification of cast alloys, development of effective composites and coatings, including nanostructured targets for coating deposition, powders for deposition of nanostructured coatings, components for composite materials, components of cast alloy modifiers, components of nanostructured wear-resistant coatings, nanoporous metallic and ceramic filters.

Today, our team proposes for practical realization the following scientific-and-technological developments:

• technological processes for production of nanosized powders of elements (tungsten, tantalum, niobium, molybdenum, nickel, cobalt, iron, copper) and their compounds (oxides, carbides, nitrides) as well as composites with set disperse, chemical and phase compositions in the thermal plasma of electric arc discharge.

The average size of produced nanopowders is lies in 20–100 nm range;

• fundamentals of technology for development of nanostructured hard alloys of tungsten carbide-cobalt with dramatically increased hardness and wear-resistance for application in cutting tool manufacture. Production of hard alloys in concentration range from VK-1 to VK-15 with introduction of complex grain growth inhibitors (Figure 7);

• development and manufacture of plasma-chemical installations for synthesis of metal and compound nanopowders of 30, 100, 300 kW power (efficiency 0.5–1.0; 5–10; 30–50 kg/h) using electric arc plasma generators;

• designing of shop areas for production of nanopowders on the basis of plasma-chemical units;

• investigations, directed on development of materials for production of high-capacity electrolytic condensers based on nanopowders of tantalum and niobium, nanopowder modifiers of cast iron, steel and alloys providing reduction of size of metal crystalline structure at 0.05–0.1 % weight fraction.

• composite materials with nanopowder application;

• nanopowder coloring agents;

• nanostructured coatings by means of plasma spraying of materials, manufactured with nanopowder application;

• nanostructured metallic and composite conductors with specific electro-magnetic properties;

• catalyzers of fuel elements.

Toxicological properties of nanopowder materials were investigated in order to provide safe operation of nanostructure objects. The risk and possibility of secure production, application and recycling of nanomaterials were estimated. A database of bio-safety existing nanomaterial was created. Developed were the methodological approaches to hygienic standardization and certification of manufacturers, goods and services in area of nanotechnology.

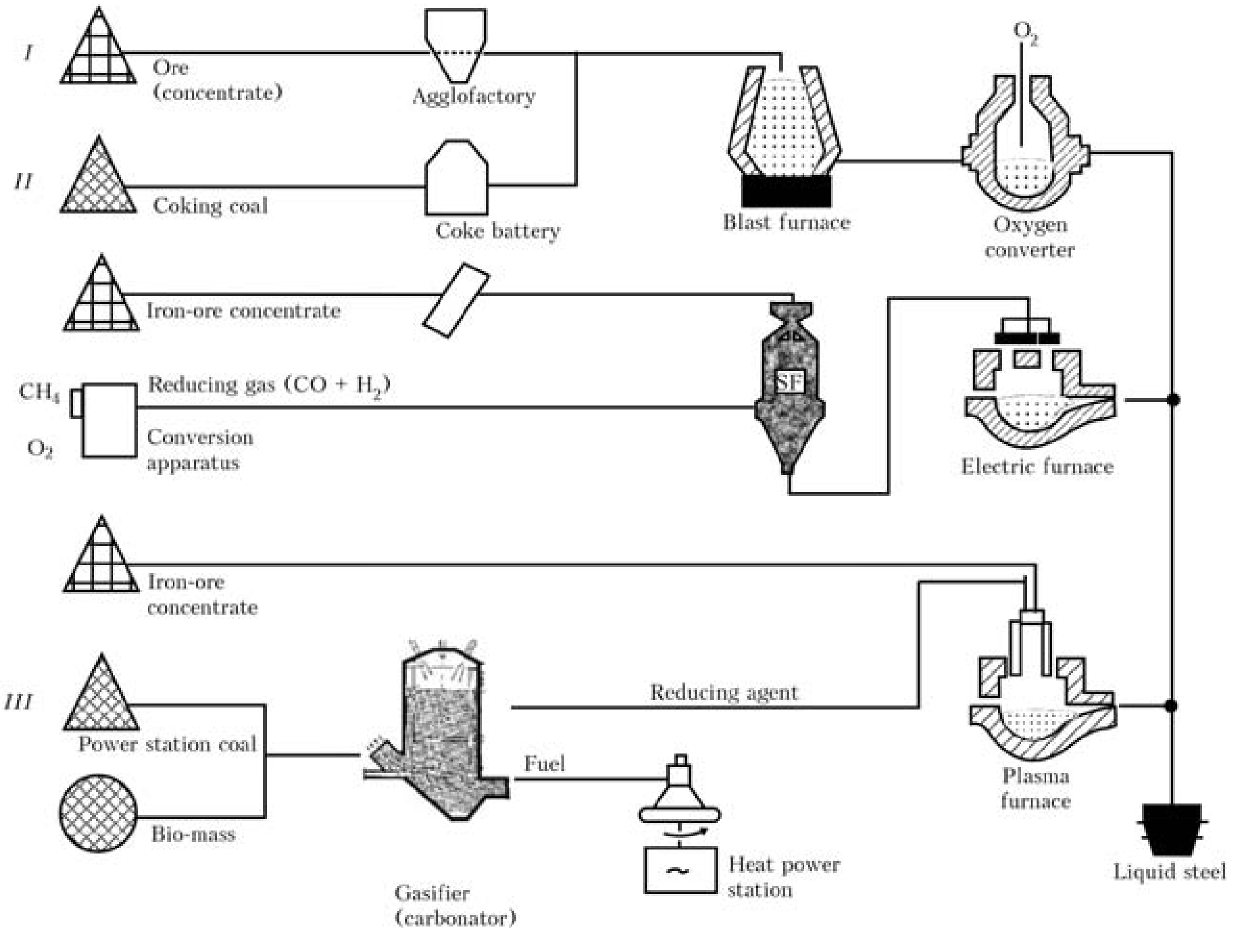

Figure 8. Steel production scheme

Some processes with the thermal plasma effect on gas media, melts and solutions, including applicable for processes of technogenic raw material treatment were investigated, among which is a plasma-catalytic reforming of hydrocarbon raw materials for production of hydrogen-containing gases and oxidation of organic additives in the water.

Current steelmaking, performed on blast furnace-converter (Figure 8) equipment-technological scheme, has series of significant disadvantages. The latter are determined by the necessity of compliance to high requirements of raw material and its special preparation, since specific nature of the blast-furnace process requires feeding in the blast furnace of the material with high level of mechanical properties in combination with gas permeability providing. The agglomeration and by-product-coke production, which use expensive and scare coking coal, not only raise the price of manufacture in whole, but cause environmental damage. It can achieve 25 % of prime cost of steelmaking based on value estimation. Proposed alternative processes, in particular the method of direct reduction, which has found industrial application in the domestic metallurgy, could not significanfly replace the traditional steelmaking technology, based on blast furnace process, by number of reasons, including due to the energy consumption. It is assumed that application of plasma technique can have a positive role in possible transformation of the steelmaking production. It can be used at the stage of production of reducing agent and fuel from low-grade organic raw material by means of its gasification for pollution-free heat power station as well as in the reducing installation.

We develop a concept of energy technology of future. It is based on development of pollution-free energy-technological complex on modular principle, combining energy production and chemical-metallurgical production of metals, alloys and compounds from natural technogenic raw materials (Figure 9) on plasma technique basis. At that, significant decrease of energy consumption is predicted in comparison with traditional and alternative methods.

Development of the plasma energy-metallurgical complex will allow 1.5–2.0 time reduction of energy intensity of steelmaking; use of power station coal and hydrocarbon-containing wastes as a primary power source; decrease the detrimental effect on environment due to absence of by-product-coking and agglomeration produc-

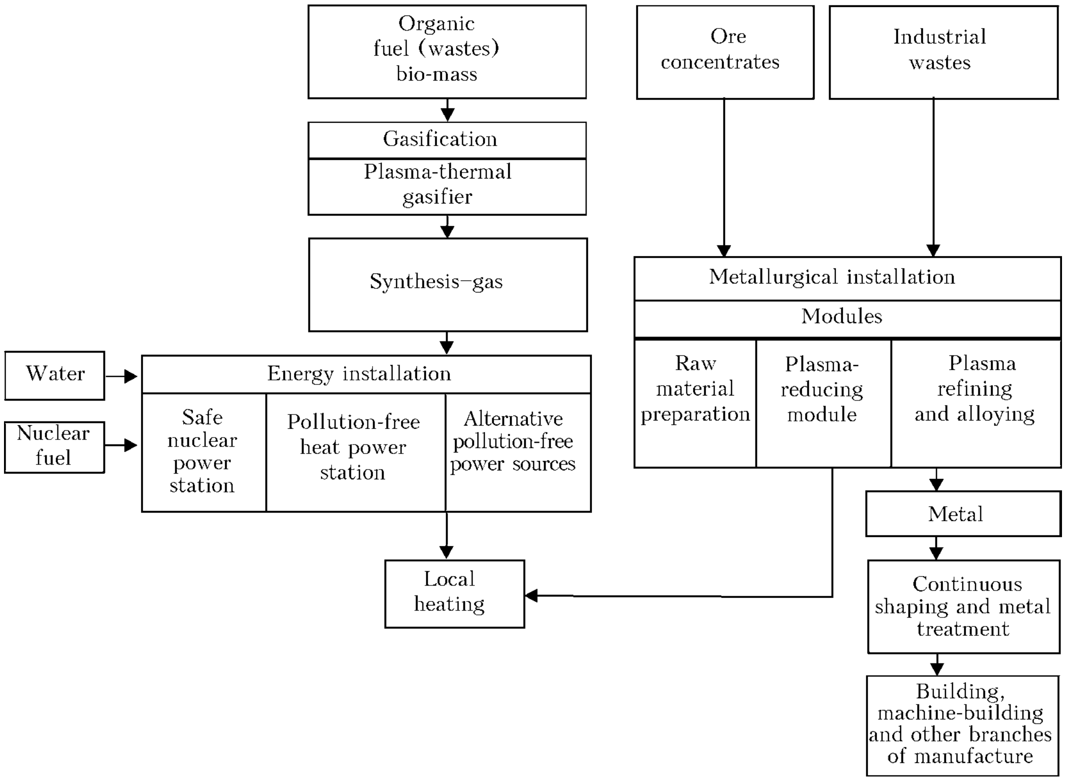

Figure 9. Principle scheme of energy-metallurgical complex

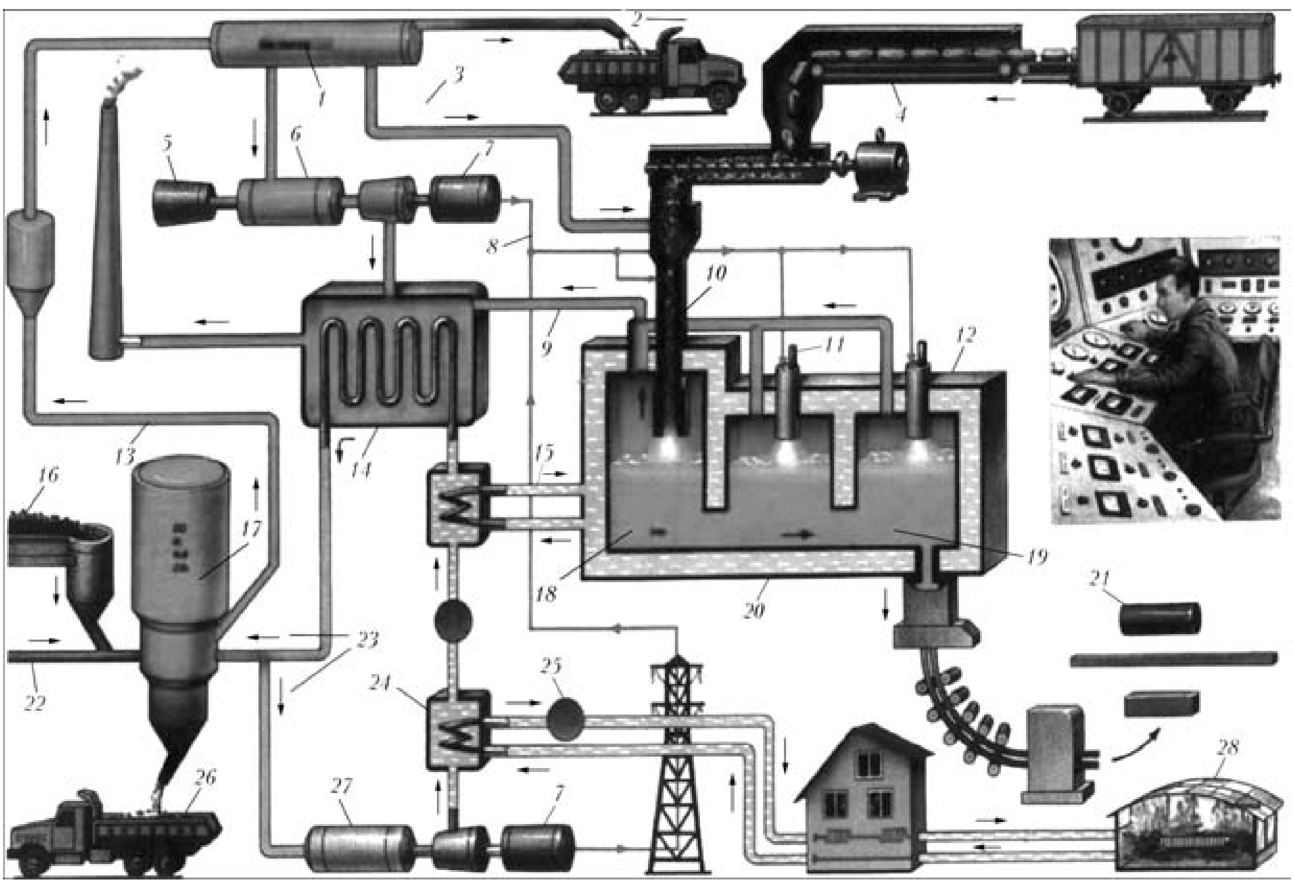

Figure 10. Scheme of predicted metallurgy of future: *1* — gas cleaning, *2* — sulfur; *3* — reducing gas; *4* — iron-ore concentrate; *5* — compressor; *6* — gas turbine; *7* — generator; *8* — electric power supply; *9* — exhaust gas; *10* — plasmatron (reduction); *11* — plasmatron (cleaning); *12* — plasmatron (alloying); *13* — gasifier; *14* — boiler; *15* — water; *16* — coal; *17* — CO, H_2, H_2O, CO_2; *18* — iron; *19* — steel; *20* — metallurgical block; *21* — rolled metal; *22* — oxygen; *23* — vapor; *24* — heat exchanger; *25* — pump; *26* — ash; *27* — steam turbine; *28* — greenhouse

tions; expand the raw material base, fully apply crude ore, develop the multi-goods metallurgical production, including nanostructured materials; create self-contained ecosystem complex — housing estate.

Physical-chemical and energy-physical fundamentals of the processes for coke-free plasma-arc production of metals of iron group from dispersed oxide raw material were developed applicable to the problem of optimization of structural-technological arrangement of the complex reducing module. Applicability of the process of plasma liquid-phase reduction to complex crude ore of titanium-magnetite type was demonstrated. Developed are the recommendations for completing of statement of work on development and manufacture of the pilot-industrial plasma-arc liquid-phase furnace of 3–5 MW power for iron reduction from titanium-magnetite concentrate.

A perspective scheme of metallurgy of future (Figure 10) is proposed for realization based on the developed concept of calculation and experimental investigations, aimed at development of the optimum structural arrangement of energy-technological processes on plasma technique basis.

The works were carried out with the support of the Russian foundation of fundamental investigations (grants No. 11-08-00516-a, No.13-03-00733), grant of the President of RF for support of leading scientific schools (NSh-854.2012.3).

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Received 11.07.2013

CHALLENGING TECHNOLOGIES OF MANUFACTURE OF HIGHLY-RELIABLE PRODUCTS OF STRUCTURAL STEELS FOR BASIC BRANCHES OF INDUSTRY

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The main elements of new complex technologies providing the efficient production of materials with a new level of properties were considered. The prospect of development of new systems of alloying of structural materials for machine building with control of their primary crystalline structure, mechanisms of strengthening, resistance to brittle fractures was noted. 4 Tables, 10 Figures.

Keywords: *technological and materials science principles, complex technologies, structural steels, basic branches of industry, challenging research directions*

New requirements to reliability require application of new technological and materials science principles. The relation of «micro-meso-macro» parameters of structure of materials (Table 1), introduced during transition from liquid state into solid one, i.e. from the very beginning of technological route, requires application of new scientific and technological approaches to the development of new technologies. The old technologies allowed removing only rough discrepancies between the requirements and a real quality.

The industry branches which require development of new technologies and materials:

Table 1. Levels of structure

Microlevel ($\leq L_0$)	
Vacancy, atom	$2–3\cdot10^{-10}$ m
Clusters	$2–5\cdot10^{-9}$ m
Dislocation	10^{-8} m
Meso-level	
Block of mosaics, subgrain, sulphides, NI	$10^{-7}–10^{-6}$ m
Level of grain L_s	
Grain, dendrite, sulphides, NI	$10^{-5}–10^{-4}$ m
Macrolevel ($>L_s$)	
Group of grains	$2–5\cdot10^{-4}$ m
Specimen area	10^{-3} m
Specimen as a whole	More than $10^{-3}–10^{-2}$ m

Power engineering, heat power complexes, nuclear power engineering: pipelines, wind power generators, stop valves; heat resistant scarcely-alloyed materials for supercritical parameters (SCP) of work; blades for the stages of gas turbine plants (GTP); structural materials with improved working characteristics for reactor units, turbines with service life of more than 60 years;

Chemical industry: structural materials for reactors and high-pressure pipes;

Transport and main gas pipelines: new materials for railroads, ship building, pipes of high strength;

Products of defense industry.

The important stage in formation, investigation and control of properties of metal products is solidification process. It is composed of a number of physical and physical-chemical processes, where solidification stage is a key one, i.e. the phase transition itself of the first kind: liquid (melt)-solid body (crystals).

As far as all the real metallic systems, used for manufacture of products, are multicomponent, it is very important to understand the level of agitation which is introduced into regularity of crystalline structure of alloy base (iron, as in our case) by each participant of the composition. In the first turn it is rational to distinguish most strongly agitating elements. For such evaluation the most suitable is the expression, which Chalmers called the accommodation coefficient A_c:

$$A_c = e^{-\frac{\Delta H_s}{RT_m}}, \quad (1)$$

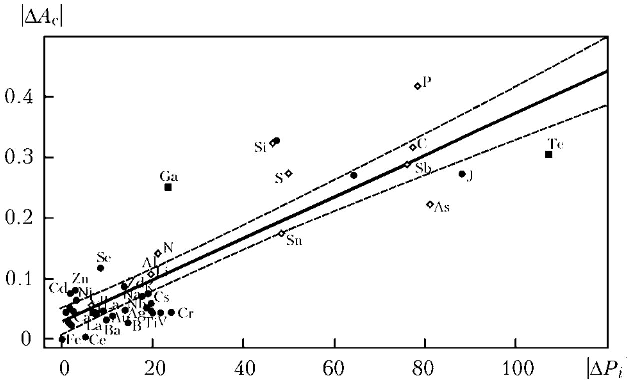

Figure 1. Relation of potential of ionization ΔP_i and ΔA_c

where A_c is the accommodation coefficient; ΔH_s is the latent heat of solidification; T_m is the solidification temperature.

In case of melting Ac is accepted equal to 1.

For quantitative measure of agitation evaluation caused by impurity during solidification, the expression was derived (2):

$$|\Delta A_c| = A_c^{Fe} - A_c^{B}. \quad (2)$$

As a result of calculation $|\Delta A_c|$ the elements having the strongest agitating influence on solidification of iron-based alloys were arranged in a row according to the level of their decrease:

P, Si, C, S, Sb, As, Bi, Sn, N, Cu, Al, Mn. (3)

The value $|\Delta A_c|$ has a good correlation with the potential of ionization ΔP_i integrally describing the thermophysical peculiarities of a single element (Figure 1).

Based on the hypothesis of two-stage mechanism of solidification process (atomic melt–cluster-atomic boundary layer — joining of clusters to crystalline front), the crystallization and influence of thermophysical (solidification rate) and physical-chemical (concentration and $|\Delta A_c|$ impurities) factors on the fractal dimension D as the characteristics of regularity of the crystalline matrix structure (Figure 2) were modeled. As is seen from the succession (3), silicon has a very strong influence on the solidification process of iron-based alloys. Figure 3 shows the results of experimental and calculation study of effect of silicon and ΔA_c on the structure of structural Cr–Ni–Mo steel.

During crystallization of steel, phosphorus has also the equally strong influence. In connection with the fact that influence of agitating elements is added, their effect is either intensified or in case of presence in the amount of less than critical concentration, it is weakened (Figure 4).

Simultaneously with the processes violating the regularity of constitution of crystalline structure, the phenomena are developed facilitating

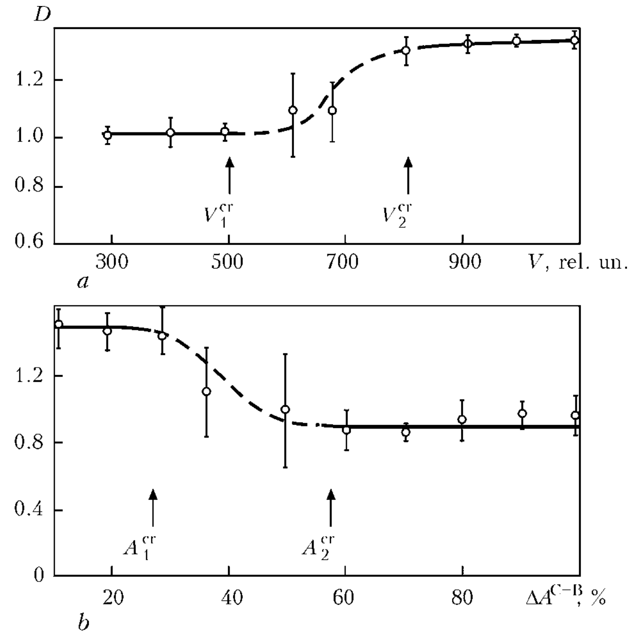

Figure 2. Dependence of fractal sizes D of model structures on the cooling rate V (*a*) and relative accommodation coefficient ΔA_c (*b*)

the decrease of resistance to degrading loads (thermal, atomic, periodically force, etc.). The data of Table 2 prove the relation between violation of regularity of constitution at the presence of definite impurity $|\Delta A_c|$ and tendency of material to embrittlement.

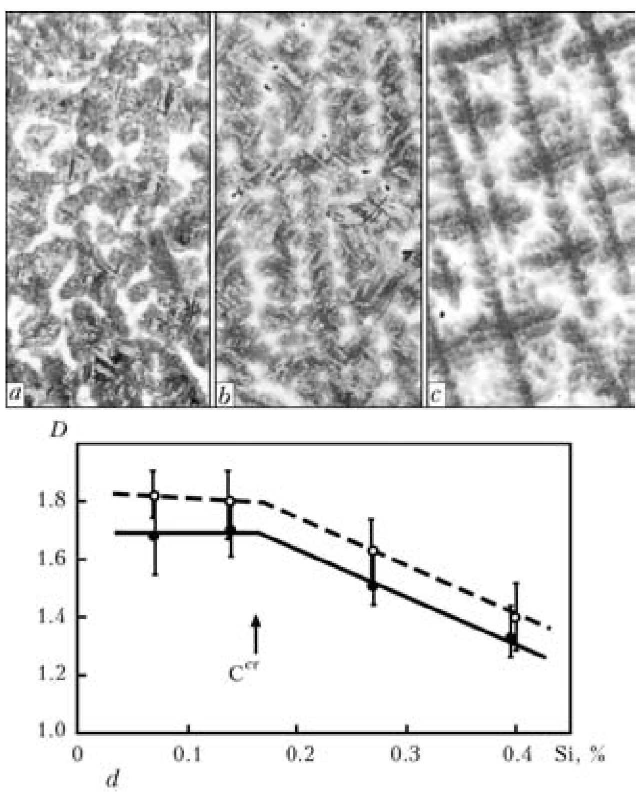

Figure 3. Microstructure of specimens at different content of silicon (*a*–*c*): *a* — 0.05 %; *b* — 0.15; *c* — 0.27; *d* — dependence of fractal sizes D of model structures on silicon content

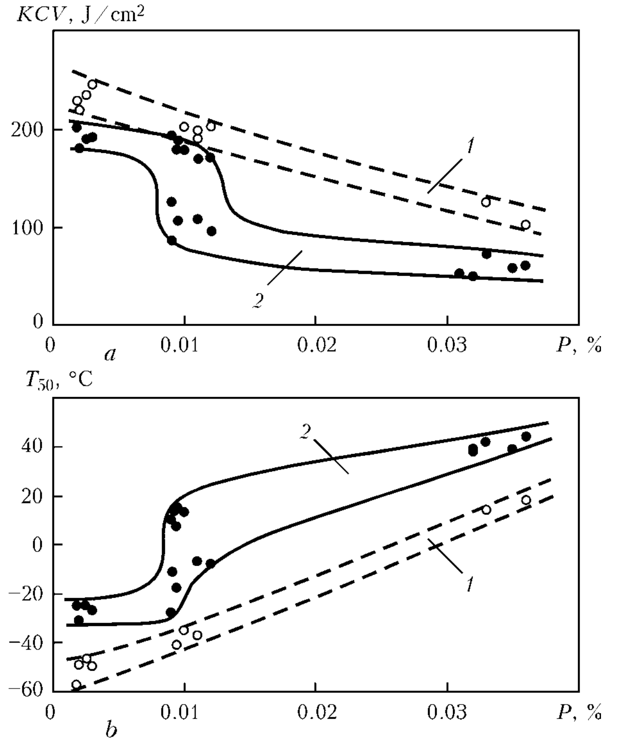

Figure 4. Influence of phosphorus and silicon on the change of impact toughness (*a*) and temperature of brittle-tough transition (*b*): *1* — <0.1 % Si; *2* — ≥0.1 % Si

The modern concepts about the nature of embrittlement of steels are based on formation of preliminary segregation (precipitates) and segregations (phosphorus, sulfur, tin, antimony and other elements) and intensifying action of alloying elements, such as silicon, nickel, manganese, the influence of which strongly depends on their concentration.

The important problem in this case is the state and extension of grain boundaries. The greatest attention was always paid to the investigation of the state of grain boundaries in the metal of body equipment of the nuclear power plants (NPP). In the last period in connection with the requirements to increase the life and reliability of these products and also to provide the competitive advantages of domestic nuclear power equipment in the OJSC SPA «CNIITMASH» the works are systematically carried out on study of mechanisms of formation of grain boundaries, evaluation of their influence on properties of products and development of technological methods of control of quality and properties of boundaries.

Using the gained experimental material, the procedure of modeling was developed to evaluate the sizes of grains of primary crystalline structure and their evolution at different operations of deformation. The work like this and in such a volume is carried out in our country for the first time.

The evaluation of elements with the strongest influence on the state of boundaries was carried out. As the example, the behavior of phosphorus, the element considerably influencing the state of boundaries at all the stages of technological route and during service, was studied. As is known, phosphorus is the element the accommodation coefficient of which is strongly differed from that of iron. Therefore it is a strongly liquating element, the equilibrium distribution coefficient of which is very low during crystallization (K_0 is less than 0.1). Due to this, during solidification of large ingots used in production of body equipment of the nuclear power plants, this element is non-uniformly distributed accumulating itself in the interdendrite spaces (microliquation) and in the zones of chemical heterogeneity (sub-crop zone and in the zone of out-of-centre liquation). The thermodynamic approaches are known, which allow observing the changes in phosphorus concentration. The calculated values show the concentration level of impurity which can be expected at boundaries in the product made of a relatively large ingot with the average radius of more than 400 mm.

It should be noted also that as far as K_0 is the thermodynamic characteristic, it was assumed that it does not depend or scarcely depends on the concentration of liquating element. However in the recent works, including the works of associates from the OJSC SPA «CNIITMASH», it was shown, that in case of impurity concentration in the melt approximating to the solubility limit of this element in solid iron, the values K_0 grow abruptly.

Considering these approaches and experimental results on study of dendritic structure of cast steel 15Kh2NMF, the concentration of phosphorus in the boundary layer was calculated which is the pre-image of boundaries in the future product (proto-boundary), and at the final stage it

Table 2. Dependence between $|\Delta A_c|$ and embrittlement of low-alloyed steels

Parameter	Fe	Cu	N	C	Si	P
A_c	0.360	0.303	0.503	0.042	0.037	0.778
$\lvert\Delta A_c\rvert = \lvert\Delta A_c^B\rvert - \lvert\Delta A_c^{Fe}\rvert$	0	0.057	0.143	0.318	0.323	0.418

is the level of filling the boundary layer with phosphorus atoms depending on the grain size.

The investigations showed that the degree of filling the sites, suitable for absorption, with phosphorus by 0.1 results in increase of critical temperature of brittleness by 27–28 °C. As a result it was succeeded to obtain dependence of effect of phosphorus content in metal before solidification and grain size of a ready product on the increase of critical temperature of brittleness. The results of ΔT_{k0} changes are presented in Figure 5. It is important that manufacture of ready-metal products of steel 15Kh2NMF the grain size which is higher than the definite one (more than 6–8 marks) provides high stability against brittle fractures, and decrease of phosphorus content in initial metal to less than 0.004 % makes steel almost insensitive to the degrading effects.

The progress in manufacture of highly-reliable products, for example, of bodies of nuclear and oil chemical reactors, welded rotors, etc. is connected also with the further promotion of decrease in T_{k0} of weld metal. The OJSC SPA «CNIIT-MASH» developed the program of technological and organization measures, including, for example, modernization of production of fused fluxes.

It is known that the weld metal has a number of peculiarities as compared to the base metal, as far as it is serviced in a cast state. The embrittlement of Cr–Ni–Mo welds (Ni << 1.5 %, P << << 0.012 %) at delayed cooling during tempering is predetermined by the content of silicon, manganese and nitrogen above the definite level (Figure 6). The technological measures of solution of task as-applied to the body of WWER-1000 are mostly known and achievable at present:

• Restriction of nitrogen content is achieved by degassing in melting steel for welding wire;

• Restriction of silicon and manganese content in steel for wire;

• Control of transition of silicon and manganese in the process of welding into the zone «slag-welding pool» by regulation of electric parameters of welding mode;

• Purposeful creation of combination «melting of wire-flux batch» (instead of selective application of accidental flux batches).

To realize the scientific developments is only possible by the use of new technological processes or by system application of formerly prepared technological solutions, combining them in the strictly determined standard consequence and alternating them with the newly recommended procedures:

The basic elements of new technologies:

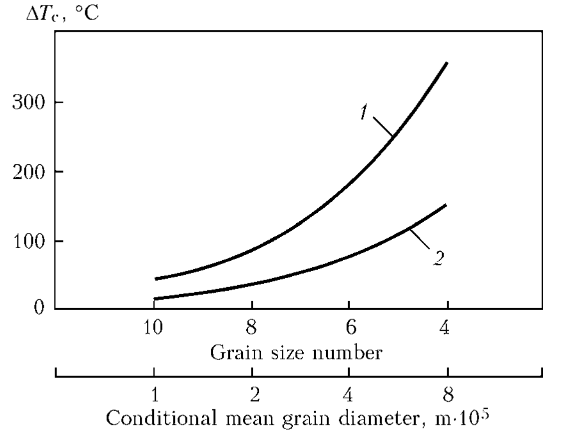

Figure 5. Influence of phosphorus content in metal before solidification and grain size of ready-made product on the increase of critical temperature of brittleness: *1* — initial concentration of phosphorus in liquid metal 0.01 %; *2* — 0.003

Steel melting cycle:

• Modern equipment for charge preparation, the modern charge materials strictly controlled as to their composition, type and sizes;

• Modern steel melting equipment providing efficient melting, strictly controlled oxidized processes (decarburizing, deep dephosphorizing) or absence of oxidation (complete remelting);

• Modern equipment for ladle treatment of liquid semi-product providing degassing, intensive fulfillment of reduction reactions (deep desulphuration, deoxidation, control of oxidation and control of oxide morphologies), precise alloying, strictly controlled heating and intensive stirring.

Cycles of solidification and pouring:

• Application of specialized fixture, which provides its optimal heat work and rational use of cast billet (shape of ingot corresponding to the product purpose);

• Application of rational method of casting (from the top, siphon, in vacuum or specialized atmosphere);

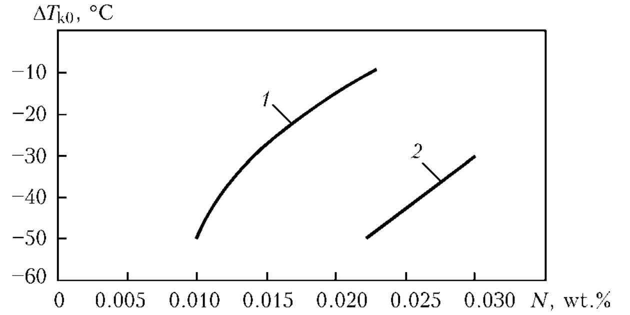

Figure 6. Influence of nitrogen content on transition temperature of brittleness of weld metal T_{k0} depending on the total concentration of silicon and manganese 0.7 % (*1*) and 0.6 (*2*)

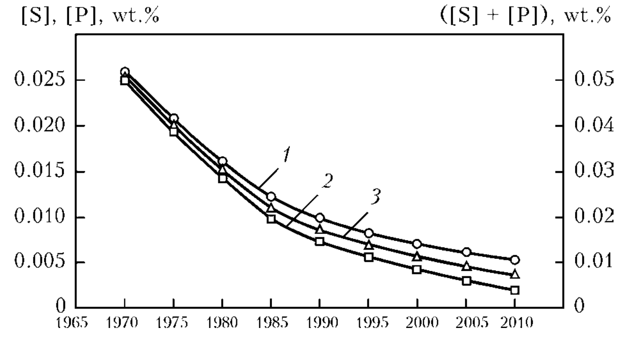

Figure 7. Dynamics of changes of admissible content of impurities in the steels for power machine building: *1* — [P]; *2* — [S]; *3* — [P] + [S]

• Standard state of liquid metal before pouring (strictly regulated chemical compound, oxidation, hydrogen content, temperature);

• Protection against contact with environment (protection against secondary oxidation, saturation with hydrogen and nitrogen);

• Differentiated and controllable temperature-speed mode of pouring.

Deformation processing:

• Modern furnace, forge-press equipment, providing necessary distribution of temperatures before deformation accounting for accumulated deformation and its speed;

• Modern fixture, measuring electron tool;

• Program deformation considering the data about quality and peculiarities of initial billet (ingot, ESR ingot, forged billet).

Heat treatment:

• Differentiated modes considering the results of evaluation of characteristics of an ingot (chemical composition, hydrogen content, amount of inclusions) and deformed billet (maximum grain size, distribution of non-metallic inclusions and zones of chemical heterogeneity);

• Modern thermal furnaces with admissible non-uniformity of thermal field in the range of up to 5 °C, the application of vertical furnaces with the bottom installation device;

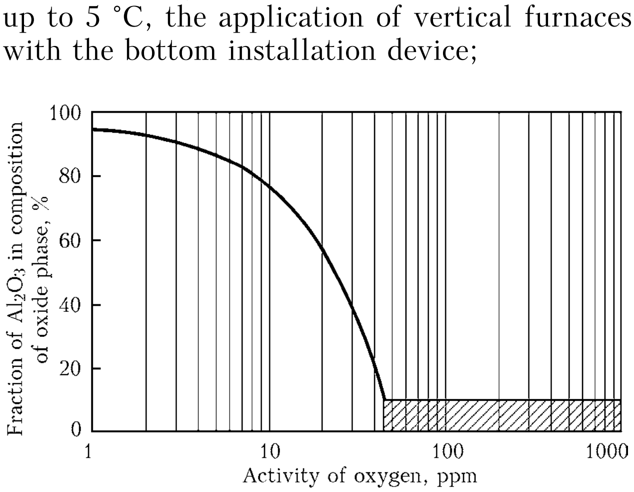

Figure 8. Influence of activity of oxygen on content of Al_2O_3 in the composition of non-metallic phase (for steel with 9 % Cr)

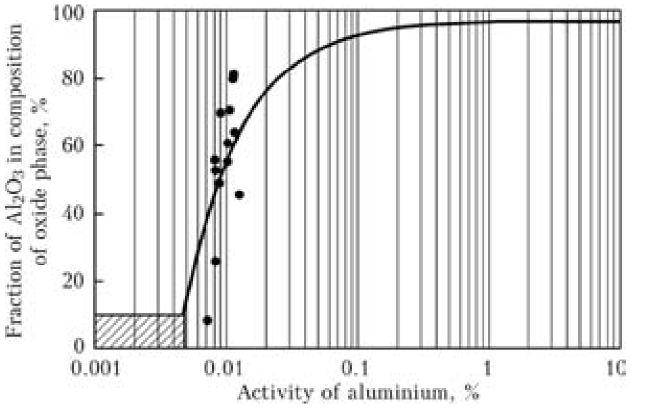

Figure 9. Influence of activity of aluminum (concentration) on the content of Al_2O_3 in the oxide inclusions of steel 15Kh2NMFA (curve was obtained under the laboratory conditions)

• Modern thermal spraying units (mostly of vertical type), modern quenching devices and media.

Welding and mechanical treatment stage:

• Modern means of control and metrological equipment;

• Welding consumables adapted to the base metal;

• Welding fluxes, providing both protection as well as formation of preset properties and quality of weld material;

• Increase of share of automated processes, application of three-coordinates welded and surfaced heads;

• Application of modern processes of finishing treatment not resulting in accumulation of stresses in the product.

Let us study some examples of application of modern technologies.

Figure 7 shows dynamics of changes in the admissible content of controllable impurities in the materials used in the nuclear and convection power engineering and other important areas of economy. The results show that for today the technology allows approaching the limit of solubility of sulfur and phosphorus in the steels and, thus, finding a radical solution of the problem

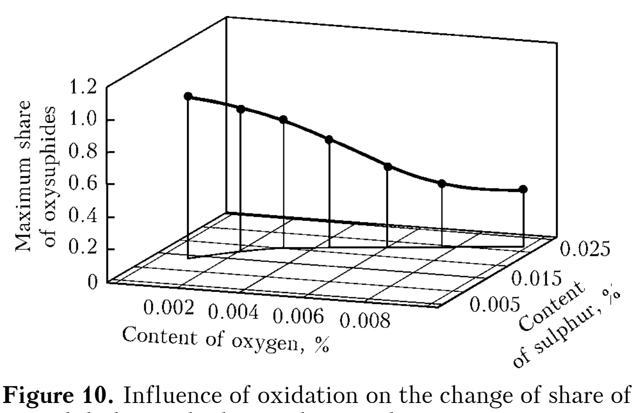

Figure 10. Influence of oxidation on the change of share of oxysulphides in the low-carbon steel

Table 3. Characteristics of the steels 15Kh2NMFA-A, 15Kh2NMFA-F of class 1

Part	Volume of sampling	Mechanical properties			
		+20 °C			
		σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %
TS 0893-013-00212179–2003 (with changes No. 2–2011)		610	490	15	55
Shells of active zone (support, upper and lower)	48	712	607	21.8	75.6
Flanges of lid and body	44	700	602	20.0	74.0
Shells of zone of pipe branches	45	691	582	21.0	75.0
Bottom of body, ellipsoid of a lid	66	715	602	20.0	73.0
Shell of zone of pipe branches for the Baltic NPS	First	670	565	24	76.0

Table 3 (cont.)

Part	Volume of sampling	Mechanical properties				T_{k0}	Notes
		+350 °C					
		σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	ψ, %		
TS 0893-013-00212179–2003 (with changes No. 2–2011)		539	441	14	50	–45 °C – for shells of active zone, –35 °C – for shells of the pipe branch zone, –20 °C – for bottom and ellipsoid, flanges of lid and body	The set values of T_{k0} are based on the real experience of manufacture of KR WWER-1000
Shells of active zone (support, upper and lower)	48	595	518	17.0	74.0	–50 – –75	For reference: 37 units WWER-1000 and WWER-1200
Flanges of lid and body	44	585	517	15.0	75.0	–50 – –80	
Shells of zone of pipe branches	45	572	495	16.0	73.0	–50 – –75	
Bottom of body, ellipsoid of a lid	66	592	517	15.0	70.0	≤–70	
Shell of zone of pipe branches for the Baltic NPS	First	547	472	16.5	72	–90	Mastering of production at PJSC «EMSS»

Note. During the whole time of production none of the shells for reactor body had any inadmissible deviations from the requirements of TS.

of chemical heterogeneity and embrittlement of structure materials connected with it.

The control of the composition and morphology inclusions in different materials for power engineering are given in Figures 8–10.

The application of number of technological solutions mentioned above allowed the improvement of technology of production of equipment for the nuclear power station to the higher level which turned to be a principally new stage in development of metallurgy both for the nuclear machine building as well as machine building in general. The increased requirements to the cleanness of metal, intensive refining, new technology of pouring, forging and heat treatment, accepted for bodies of reactors of the project NPS-2006, allowed obtaining the very low real values of critical temperature of brittleness in manufacture for all the elements of body and lid of reactor (below 90 °C) (Table 3).

Table 4. Chemical composition of steel for collectors of steam generators of the type PGV-1000MKP, wt.%

Grade of steel	C	Si	Mn	Ni	Mo	W	Cr	Cu	S	P
							Not more than			
10GN2MFA-VD 10GN2MFA-Sh	0.08–0.12	0.17–0.37	0.80–1.10	1.8– 2.3	0.40–0.70	0.03–0.07	0.30	0.30	0.005	0.008
10GN2MFA-A	0.09–0.11	0.20–0.30	0.90–1.00	1.8–2.0	0.55–0.65	0.04–0.06	0.15	0.15	0.002	0.006

Note. In steel 10GN2MFA-A the content of Sn, As, Sb and Kh = $(10P + 5Sb + 4Sn + As)\cdot 100 \le 15$ is determined.

One more example of application of new approach to the technology is the development of especially pure modifications of steel grade 10GN2MFA-A, in which the contents of sulfur and phosphorus are considerably decreased, the limits of content of basic alloyed elements are narrowed, the determination of content of arsenic, tin and antimony with regulation of X-factor (X = (10P + 5Sb + 4Sn + As)·100) (Table 4) was introduced.

It also should be noted that at the present time in the OJSC SPA «CNIITMASH» to decrease the critical temperature of brittleness and stabilization of properties in welding the investigations on determination of mechanism of effect of complex modifiers, added to the weld metal through the ceramic flux, on mechanical characteristics of weld metal are carried out.

The tests of mechanical properties of metal of welds produced in welding of pilot specimens of steel 15Kh2NMFA using pilot compositions of ceramic fluxes FTsK-16 in combination with the wire SV-12Kh2N2MAA evidence of high level of mechanical characteristics of weld metal, increasing the requirements of standard documentation. The tests in welding under the flux KV-4 showed that the critical temperature of brtittleness amounts to $T_{k0} = -30$ °C.

Conclusions

At the present time there are elements of new complex technologies which were tested and implemented providing effective manufacture of materials with the new level of properties.

The further searches in the area of complex technological and materials science investigations are directed to the creation of new systems of alloying of structural materials for machine building, oriented to the control of the primary crystalline structure, by the strengthening mechanisms, mechanisms of resistance of metals to brittle fractures.

It is necessary to develop new systems of technological and standard documentation relying also on the use of objective in-process methods and creating conditions for continuous electron monitoring of technology allowing its correction according to the in-process values obtained at the previous stage.

Received 10.06.2013

SELECTION OF WELDING TECHNOLOGIES IN CONSTRUCTION OF LARGE-DIAMETER MAIN PIPELINES

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The advantages and disadvantages of different technologies of pipes joining applied in construction of main pipelines are considered. It was noted that the method of flash-butt welding has advantages as compared to the arc, beam and hybrid methods of welding. 1 Table, 8 Figures.

Keywords: *welded pipelines, electric arc processes, beam welding methods, flash-butt welding, economic efficiency*

The industrialized countries which are in need of a large volume of natural gas are actively planning and constructing the main pipelines from gas-extracting centers to the sites of consumption. Especially it concerns such countries as Brazil, Algeria, Australia, Russia, countries of Caspian region and Middle East.

Welding is the most responsible technological operation in construction of pipelines and rate of construction depends on the efficiency of welding works fulfillment, therefore the development of welding technologies is the decisive factor, determining the quality and efficiency of construction and assembly works.

The welding processes and technologies can be divided into the following groups: electric arc, beam and press, including flash-butt welding and friction welding. The application of these technologies should provide high-quality welded joints of a new generation of pipelines of steel of higher strength category, such as X65, X70, X80 at the diameters of up to 56 inches.

Electric arc processes. Since the 1960s the manual electric arc welding (MAW) using electrodes of cellulose type for root weld and basic electrodes for filling layers. This technology is also used at present for steels of conventional class of strength. It requires high skills of welders-operators at keeping the temperature conditions of welding to remove hydrogen from the welded joint. The MAW technology will be also further used on the small areas of pipelines under the restricted conditions and repair-welding works.

The MIG/MAG welding process for producing of weld root with a controllable electrode metal transfer according to the STT method with the following filling of a groove at the conventional process is presented in Figure 1. At present this method is widely used, moreover the filling after producing of a root layer, except of using MIG/MAG process, can be performed also by electrodes with a basic type of coating. The peculiarity of this process is achievement of the very high quality of a multilayer weld, if welding was completely performed from the external side of a pipe.

To produce a weld using only MIG/MAG process (Figure 2) a number of companies carried out the research works and designed equipment

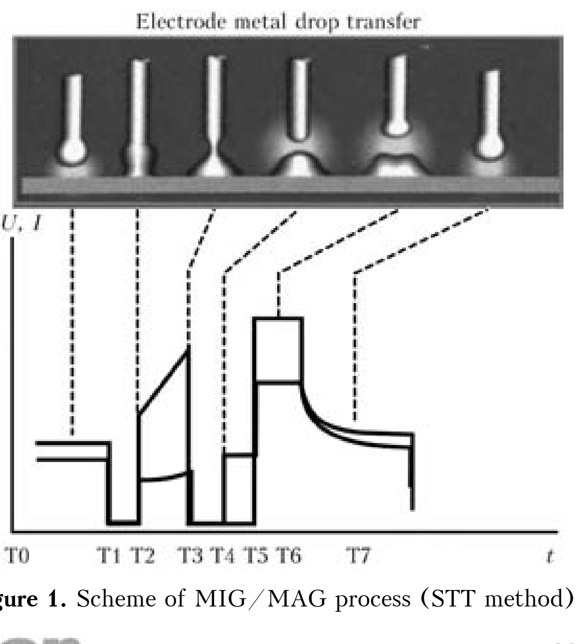

Figure 1. Scheme of MIG/MAG process (STT method)

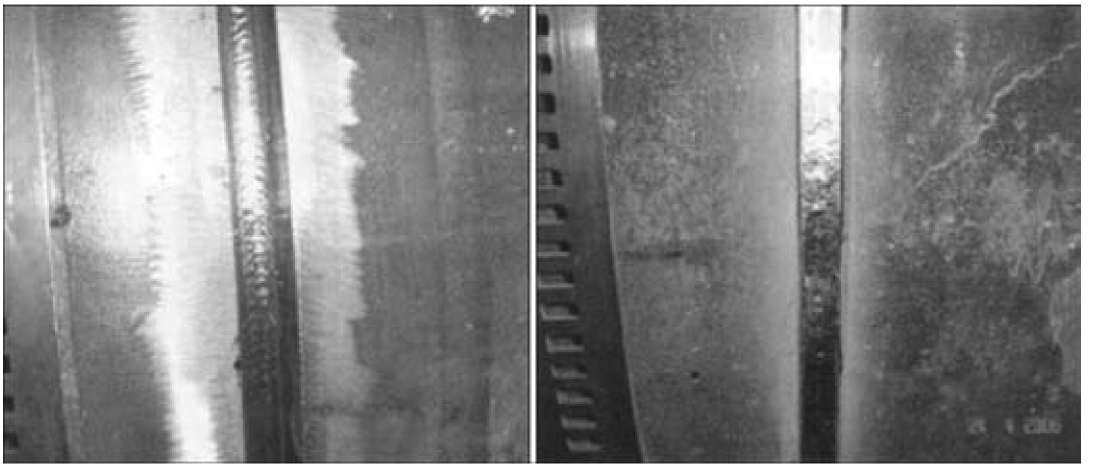

Figure 2. Appearance of welded joint produced using MIG/MAG process

for automatic orbital welding («Proteus» machines).

There are modifications, when orbital equipment is operating with two torches (Figure 3), which reduces the time of weld filling. Especially interesting is the modification of tandem MIG/MAG process representing new possibilities for the growth of efficiency. In this case one welding torch with two contact nozzles provides feeding of two wires into one common welding pool. At the present time its application under the construction and assembly conditions is restricted, first of all, due to instability of the process and, secondly, because of need in welding operators of a high skill.

For MIG/MAG process the technology with use of a welding column (Figure 4) of CRC Evans company (USA, Huston) is the most updated one. According to this technology the welded joint is produced using welding heads, arranged inside and outside of welded joint of appropriate pipes.

Requirements to circumferential welded joints produced by MIG/MAG process are specified as to very accurate geometry of abutting the pipe ends and accurate control of welding parameters. As far as deposited layer has a 3 mm thickness on one welding station, then for the thick-walled pipes, for example of 24 mm, it is necessary to organize eight welding stations to preserve the calculated cycle during performance of one welded butt. At the present moment this technology is widely used. However it requires the staff of more than 60 people attending the welding column for welding pipeline of 1420 mm diameter at the wall thickness of up to 24 mm.

Beam welding methods. Among the beam welding technologies, the most developed is the technology of hybrid laser welding. The machines developed in SLV Halle (Germany) show promising results under the laboratory conditions (Figure 5). However, to implement this technology it is still necessary to apply much efforts to modifying the equipment (Figure 6) and development of assembly and welding fixtures.

Press methods. At the regional congress of the International Institute of Welding, held in Sophia in October 20–24, 2010 all the welding

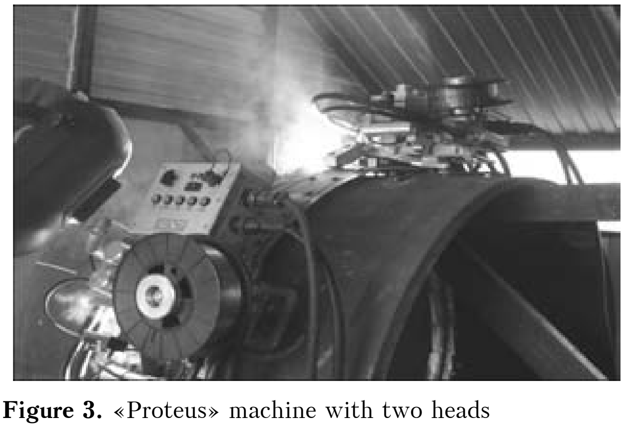

Figure 3. «Proteus» machine with two heads

Figure 4. CRC column on the route

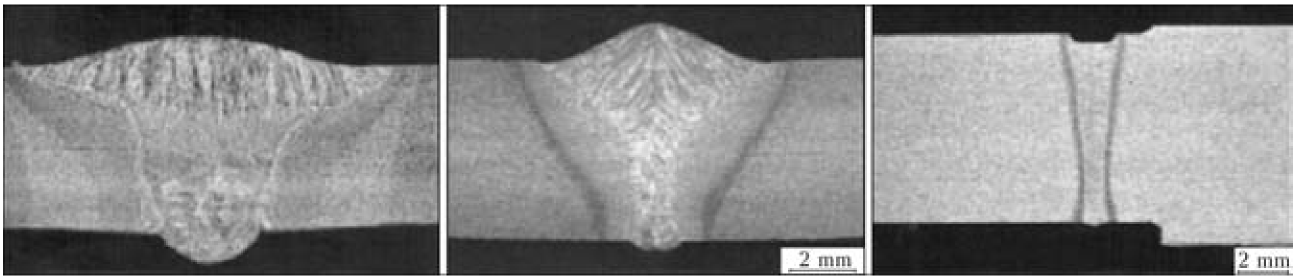

Figure 5. Macrosection of pipe steel joints produced using different power sources: *a* — MIG/MAG; *b* — MIG/MAG + laser; *c* — laser

technologies applied in construction of main pipelines were discussed.

The technology of flash-butt welding (FBW) was recognized as the most successful from the point of view of efficiency, small number of attending personnel and the lowest influence of subjective human factor. Resolution of the congress advised it as a priority implementation.

In practice the technology of FBW represents the process which provides the supply of voltage between the two ends of pipes which are aligned according to the certain program, as a result of which the flashing occurs. The power of passing current of a high value (hundreds of thousands amperes) heats the ends of pipes, after quick compression of which the permanent joint is provided.

This technology was developed at the E.O. Paton Electric Welding Institute under the supervision of B.E. Paton, S.I. Kuchuk-Yatsenko, V.K. Lebedev together with the organizations of the Ministry of Oil and Gas Industry of the USSR in the 1970s. Further, the welding machine «Sever 1» was designed on its base, with the use of which more than 1 mln. welded joints of pipes of 1420 mm diameter were produced and after 30 years of their service there was no a single case of emergency situation.

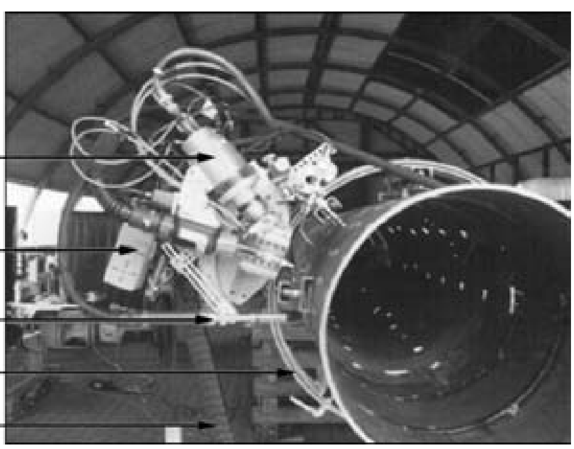

Figure 6. Welding complex for hybrid laser welding: *1* — head for hybrid welding; *2* — moving tractor with control sensor; *3* — torch in the position of groove filling; *4* — ring; *5* — hose

After 2009 the plant CJSC «Pskovelectrosvar» together with the E.O. Paton Electric Welding Institute carried out the modification of this equipment for application of this technology in welding of large-diameter pipelines. The KSS-004 complex was developed (Figure 7) which at the present time is planned to be widely used in many areas of invested pipeline system both in Russia as well as in other countries.

In accordance with the above-mentioned resolution of the IIW, some experimental welded joints of large-diameter pipes were produced, which later were tested in the laboratories of CJSC «Pskovelectrosvar» and also in the laboratories of the Institute of Materials Science of the Bulgarian Academy of Sciences. Using the computer system of control, the parameters of welding mode and modes of the following heat treatment and also parameters of removal of external and inner flash for the next automatic ultrasonic testing were precisely preset.

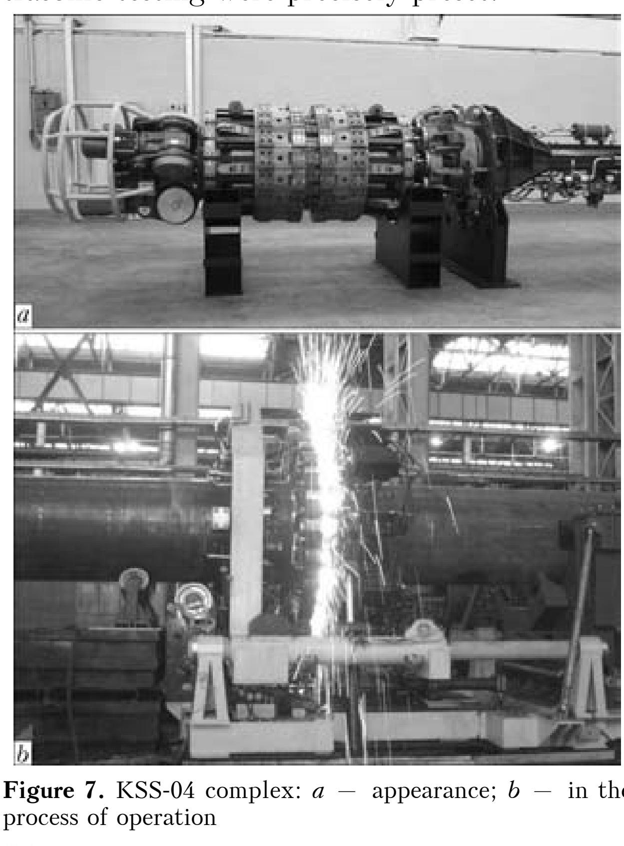

Figure 7. KSS-04 complex: *a* — appearance; *b* — in the process of operation

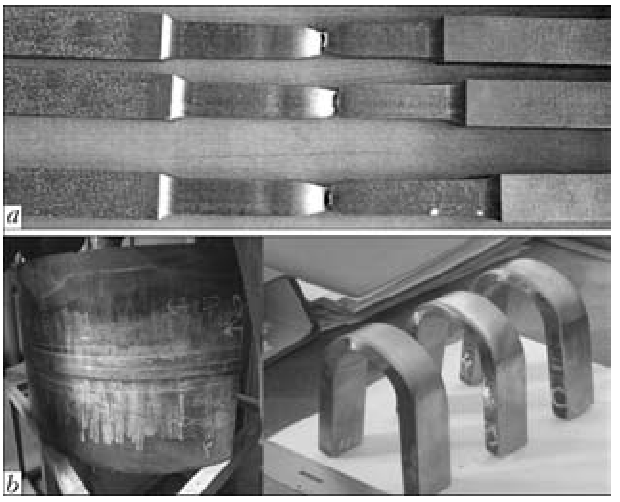

Figure 8. Appearance of specimens of pipe welded joints DN 1220×27 mm after tensile (*a*) and bending (*b*) tests

In the experiments, steel of strength category X65 of «Europipe» company (Germany) of the following chemical composition, wt.%: 0.071 of carbon, 0.237 of silicon, 1.51 of manganese, 0.005 of sulfur, 0.009 of phosphorus, 0.04 of chromium, 0.15 of nickel, 0.07 of molybdenum, 0.04 of vanadium, 0.037 of aluminium, 0.012 of titanium, 0.02 of niobium, 0.002 of boron, 0.03 of copper was used. Its mechanical properties in as-delivered state are the following: $\sigma_{0.2}$ = 490 MPa; σ_t = 553 MPa; δ = 26.5 %; KCV_{+20} = = 335.8 J/cm^2; KCV_{-40} = 334.9 J/cm^2. After tests of specimens the following strength characteristics were obtained, MPa: 538, 545, 541 and 540.

Appearance of specimens of welded joints of pipes DN 1220×27 mm after the tensile and bending tests is given in Figure 8.

Let us outline the advantages of FBW:

• Process is performed in one station;

• High rate of construction of pipelines due to a small period of welding of one butt in one station is provided, which amounts to 60–200 s depending on type and sizes of pipes, being welded, from 114 to 1420 mm diameter with up to 30 mm wall thickness. Great industrial experience of FSW in construction of different-purpose pipelines under on-land conditions was gained;

• All the process from beginning to the end is performed in automatic mode according to preset program which eliminates the subjective influence of welder on the quality of joints;

• Low level of residual stresses in welded joints is achieved, that considerably increases the corrosion resistance of such joint; mechanical properties meet the requirements of standards of industrialized countries (for example, the standard AP1-1104, USA);

• The quality of welded joints is efficiently evaluated by computerized processing of real values of welding mode parameters, created on the basis of real existing dependence «welding mode–joint quality», which is predetermined by physical peculiarities of FBW process; the validity of detection of possible defects is practically equal to 100 % including also the use of automated ultrasonic testing;

• The pipes of all the classes of strength are welded at any ambient temperature without preheating;

• Weather factors do not influence the quality of welded joints;

• The speed of pipeline construction is increased;

• Material expenses for pipeline construction are decreased.

Comparison of economic efficiency of implementation of flash-butt welding complex of KSS-04 type and welding column CRC Evans

Characteristic	CRC Evans	KSS-04
Pipeline extension, km	100	
Pipeline diameter, mm	1420	
Pipeline wall thickness, mm	≤25	
Cost of one complex, USD	5,750,000	3,930,000
Total number of butts on the whole pipeline considering the possible rejections, pcs	9,180	9,116
Number of project personnel, persons	68	16
Cost of welding of one butt, USD	874	579

The data given in Table have a significant evidence of advantages of application of KSS-04 complex as compared to the welding column CRC. The comparison of such factors as number of attending personnel, cost of one welded joint is especially demonstrative in favor for KSS-04 complex.

Basing on this fact, the companies, for example Bulgarian ones, which deal with realization of projects on construction of large-diameter pipelines, will be oriented to further application of KSS-04 complexes.

Received 01.04.2013

RESIDUAL STRESS MANAGEMENT IN WELDING: MEASUREMENT, FATIGUE ANALYSIS AND IMPROVEMENT TREATMENTS

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Residual stress (RS) management is a concept according to which three major stages, i.e. RS determination, RS fatigue analysis and RS beneficial redistribution are considered and evaluated, either experimentally or theoretically to achieve the optimum performance of welded structures. All three stages as well as a number of new engineering tools such as ultrasonic computerized complex for residual stress measurement, UltraMARS, software for analysis of the effect of residual stresses on the fatigue life of welded elements, ReSIsT, and new technology and, based on it, compact system for beneficial redistribution of residual stresses by ultrasonic impact treatment, UltraPeen, will be discussed. Examples of industrial applications of the developed engineering tools for residual stress analysis and fatigue life improvement of welded elements and structures will be given. 10 Ref., 8 Figures.

Keywords: *ultrasonic measurement, residual stress, software, prediction of fatigue life, redistribution of stresses, ultrasonic impact treatment, industrial application*

Residual stress management. Residual stress management is a concept that addresses major aspects of residual stresses in welds and welded structures. According to the concept three major stages, i.e. RS determination, RS analysis and RS redistribution are considered and evaluated, either experimentally or theoretically to achieve the optimum performance of welded structures.

Residual stress can significantly affect engineering properties of materials and structural components, notably, fatigue life, distortion, dimensional stability, corrosion resistance etc. Such effects usually lead to considerable expenditures in repairs and restoration of parts, equipment and structures. For that reason, the residual stress analysis is a compulsory stage in the design of structural elements and in the estimation of their reliability under real service conditions.

Systematic studies had shown that welding residual stresses may lead to a drastic reduction in fatigue strength of welded elements. In multicycle fatigue ($N > 10^6$ cycles) the effect of residual stresses can be compared with the effect of stress concentration. Even more significant are the effects of residual stresses on the fatigue life of welded elements in the case of relieving harmful tensile residual stresses and introducing beneficial compressive residual stresses in the weld toe zones. The results of fatigue testing of welded specimens in as-welded condition and after application of ultrasonic peening showed that in case of non-load caring fillet welded joint in high strength steel, the redistribution of residual stresses resulted in approximately two-fold increase in the limit stress range [1, 2].

The residual stresses, therefore, are one of the main factors determining the engineering properties of materials, parts and welded elements and this factor should be taken into account during the design and manufacturing of different products. Although certain progress has been achieved in the development of techniques for residual stress management, a considerable effort is still required to develop efficient and cost-effective methods of residual stress measurement and analysis as well as technologies for the beneficial redistribution of residual stresses.

It is very important to consider the problem of residual stress as a complex problem including, at least, stages of the determination, the fatigue analysis and the beneficial redistribution of residual stresses. The combined consideration of the above-mentioned stages of residual stress analysis gives rise to so called residual stress management (RSM) concept approach. The RSM concept includes the following main stages:

• *Residual stress determination*. The stresses can be evaluated directly through measurements either using destructive method or non-destructive method and through computation.

• *Analysis of the residual stress effects*. The effect of residual stresses can be evaluated either through experimental studies or via computational methods.

• *Residual stress modification, if required*. The modification of the residual stresses could be performed through changes in the technology of manufacturing/assembly and/or through application of stress-relieving techniques.

A number of new advanced engineering tools for all three stages of RSM were developed recently at Structural Integrity Technologies (SINTEC) Inc. located in Markham, Canada in cooperation with Ukrainian scientists. Short descriptions of the new engineering tools for residual stress management and examples of their practical application are presented below.

Residual stress measurement. *Current situation with residual stress measurements.* Over the last few decades, various quantitative and qualitative methods of residual stress measurement have been developed. In general, a distinction is usually made between destructive and non-destructive techniques [2].

The first series of methods is based on destruction of the state of equilibrium of the residual stress after sectioning of the specimen, machining, layer removal or hole drilling. The redistribution of the internal forces leads to local strains that are measured to evaluate the residual stress field. The residual stress is deduced from the measured strain using the elastic theory (analytical approach or finite element calculations). Among the most commonly used methods one can mention a few like:

- The hole drilling method;
- The ring core technique;
- The bending deflection method;
- The sectioning method, etc.

The second series of non-destructive methods of residual stress measurement is based on the relationship between the physical and the crystallographic parameters and the residual stress. The most developed methods are:

- *The X-ray and neutron diffraction methods*. These methods are based on the use of the lattice spacing as the strain gauge. It allows studying and separating the three kinds of residual stresses. Currently, the X-ray method is the most widely used non-destructive technique for residual stress measurements.
- *The ultrasonic techniques*. These techniques are based on variations in the velocity of ultrasonic wave propagation in the materials under the action of mechanical stresses.
- The magnetic methods. These methods rely on the interaction between magnetization and elastic strain in ferromagnetic materials. Different magnetic properties can be studied: permeability, magnetostriction, hysteresis, and Barkhausen noise.

While there are various destructive and non-destructive methods to detect and quantify the residual stresses described in technical literature, new industrial problems, new geometrical and material complexities related to them, combined with a general need for fast and economical residual stress measurements create strong demand in new effective techniques and devices that is increasing dramatically. The most desired technology must be reliable and user-friendly, i.e. it should not require guessing and intuition from the engineer/technician and it must be computerized for quick analysis. One such new system for residual stress measurement that is based on using of the ultrasound is described below.

Ultrasonic computerized complex for residual stress measurement. The ultrasonic computerized complex (UCC) was developed for residual stress measurement in laboratory and in field conditions [3–5]. The UCC «UltraMARS» (ultrasonic measurement of applied and residual stresses) includes a measurement unit with supporting software and an optional laptop with an advanced database and an EXPERT SYstem (ES) for analysis of the influence of residual stresses on the fatigue life of welded elements (Figure 1). The UCC allows determining uni- and biaxial applied and residual stresses for a wide range of materials and structures. In addition, the developed ES can be used for calculation

Figure 1. Ultrasonic computerized complex for residual and applied stress measurement: *a* — UltraMARS® model shown with a laptop and an oscilloscope; *b* — next generation UltraMARS®-7 model shown with all transducers, transducer holders and attachments

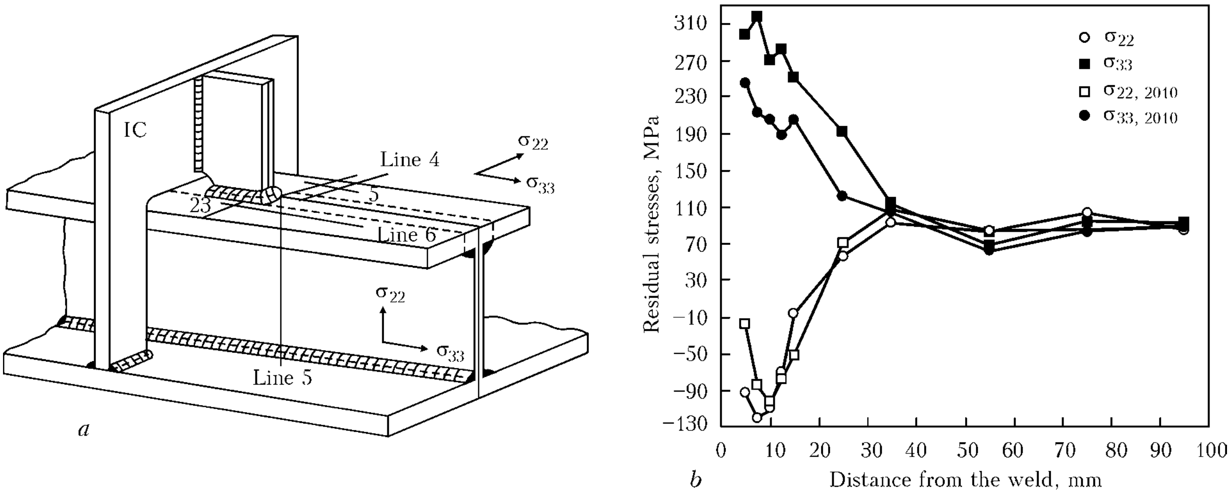

Figure 2. Measurement of residual stresses in a fragment of a real ship structure: *a* — schematic view of a fragment of the welded panel with details on residual stress measurement zones. The measurements were conducted along lines 4, 5 and 6; *b* — the distribution of residual stress along the welded stiffener (along line 6) in the welded panel before and after 2010 cycles of loading

of the effect of measured residual stresses on the fatigue life of structural elements, depending on the mechanical properties of the used materials, the type of welded elements and the parameters of cyclic loading.

The supporting software allows controlling the measurement process, storing the ultrasonic measurement data and calculating and plotting the residual stresses distribution. The software allows the use of the designed method and equipment with standard PCTs.

The main technical characteristics of the measurement unit:

• The stress can be measured in materials with thicknesses 2–150 mm;

• The error of stress determination (from external load) is 5–10 MPa;

• The error of residual stress determination is ~0.1 σ_y (MPa);

• The stress, strain and force measurement can be performed in fasteners (pins) 25–1000 mm long;

• The system can be powered from an independent power supply (accumulator battery 12 V);

• The overall dimensions of the measurement instrument 300 × 200 × 150 mm;

• The weight of the unit with transducers is 6 kg.

One of the main advantages of the developed system UltraMARS® technique and equipment is the possibility to measure the residual and applied stresses in samples and real structure elements. Such measurements were performed for a wide range of materials. An examples of practical application of the developed ultrasonic technique and equipment for residual stress measurement in welded elements is presented below.

Figure 2, *b* shows the distribution of residual stress in large scale welded panel shown sche-

Figure 3. Application of the UltraMARS system for measurement of residual stresses in the zones of welded elements of a highway bridge (*a*) and a submarine pressure hull (*b*)

matically in Figure 2, *a* along the welded stiffener in as-welded condition and after cyclic loading [6]. It can be seen from Figure 2 that the maximum residual stress near the welds (4–5 mm away from the weld) acting in the direction of longitudinal attachment and applied load reach levels 290–320 MPa that are close to the yield strength of considered material both in specimens and in the panel.

Figure 3 shows two other typical examples of field application of the Ultrasonic Computerized Complex — UltraMARS® on a section of a highway bridge and on a section of a submarine hull.

Residual stress in fatigue analysis. Despite the fact that the residual stresses have a significant effect on the strength and reliability of parts and welded elements, their influence is not sufficiently reflected in corresponding codes and regulations. This is, mainly, because the influence of residual stresses on the fatigue life of structural elements depends greatly not only on the level of residual stresses, but also on the mechanical properties of used materials, the type of welded joints, the parameters of cyclic loading and on other factors [1, 2]. Presently elaborate, time-and labor-consuming fatigue tests of large-scale specimens are required for this type of analysis.

Generally, in modern standards and codes on fatigue design [7] the presented data correspond to the fatigue strength of real welded joints including the effects of welding technology, the type of welded element and the welding residual stresses. Nevertheless, in many cases there is a need to consider the influence of welding residual stresses on the fatigue life of structural components in greater details. These cases include use of the results of fatigue testing of relatively small welded specimens without high tensile residual stresses, analysis of effects of such factors as overloading, spectra loading, application of the improvement treatments, etc.

An expert system for fatigue assessment and optimization of welded elements «ReSIsT» was developed to resolve the above-mentioned problem [2]. The ES «ReSIsT» (residual stresses and improvement treatments) is based on the original predictive model for analysis of the influence of the residual stresses and their redistribution under the effect of cyclic loading and improvement treatments on the fatigue life of welded elements.

The optimization of welded elements is based on their fatigue assessment in the dialog mode. The following important parameters of welded structures are analyzed with the goal to enhance the fatigue performance:

- Material selection;
- Preferred design of welded elements;
- Weld processes and materials;
- Residual stresses;
- Application of improvement treatments;
- Influence of possible repair technologies;
- Realistic service conditions.

The ES includes a package of programs allowing to perform storing, classifying and statistical processing of the fatigue testing results and subsequent comparative analysis of the fatigue life of welded elements in the initial condition (after welding) and after application of improvement treatments. The developed ES includes the possibility to assess through calculations the effect of welding residual stresses and the application of improvement treatments on the fatigue life of welded elements without having to perform the time and labor consuming fatigue tests. The application of heat-treatment, vibration treatment, overloading, ultrasonic peening and other improvement treatments are considered. During fatigue assessment, the mechanical properties of the materials, the type of welded elements and stress concentrations, as well as the cyclic loading parameters are taken into account. A detailed analysis of the influence of residual stresses and their redistribution under the effect of cyclic loading in the zones of stress concentration is performed during such assessment.

The significant increase in the fatigue strength of parts and welded elements can be achieved by beneficial redistribution of residual stresses. To demonstrate this point, the calculated fatigue curves for a transverse loaded butt weld with different levels of initial residual stresses are shown in Figure 4. The fatigue curve of the welded element will be located between lines *1* and *2* in the case of partial removal of tensile residual stresses (i.e. lines *3* and *4*). The decrease of the residual stresses from initial high level (line *1*) to 100 MPa (line *4*) causes, in this case, an increase of the limit stress range at $N = 2\cdot10^6$ cycles from 100 MPa to 126 MPa.

The relieving of the residual stresses in welded element to the level of 100 MPa could be achieved, for example, by heat treatment or overloading of this welded element at a level of external stresses equal to $0.52\sigma_y$. As a result, this fatigue Class 100 welded element becomes the fatigue Class 125 element [7]. After modification of welding residual stresses, the considered welded element will have an enhanced fatigue performance and, in principle, can be used instead of transverse loaded butt weld ground flush to plate (No. 211) or longitudinal weld (No. 312

and 313) [7]. Introducing of compressive residual stresses into the weld toe zone can increase the fatigue strength of welded elements even to a larger extend (lines *5* and *6* in Figure 4).

Residual stress modification. In many cases, the beneficial redistribution of residual stresses can improve drastically the engineering properties of parts and welded elements. The detrimental tensile residual stresses could be removed and beneficial compressive residual stresses could be introduced into the subsurface layers of treated materials by application of heat treatment, overloading, hammer peening, shot peening, laser shock peening, etc. One of the new processes for effective redistribution of residual stresses is ultrasonic impact treatment (UIT) or ultrasonic peening (UP) [8–10].

The UIT/UP produces a number of beneficial effects in metals and alloys. Foremost among these is increasing the resistance of materials and welded elements to surface-related failures, such as fatigue, fretting fatigue and stress corrosion cracking. The beneficial effect is achieved mainly by relieving of harmful tensile residual stresses and introducing compressive residual stresses into surface layers of metals and alloys, decreasing of stress concentrations in weld toe zones and the enhancement of the mechanical properties of the surface layers of the material. The fatigue testing of welded specimens showed that the UIT/UP is the most efficient improvement treatment as compared with traditional techniques such as grinding, TIG-dressing, heat treatment, hammer peening, shot peening etc. [1, 10]. A new advanced system UltraPeeno (Ultrasonic Peening) for UIT/UP of parts and welded elements is shown in Figure 5.

For the effective application of UIT/UP, depending on the above-mentioned factors, a software package for optimum application of ultrasonic peening was developed that is based on an original predictive model.

In the optimum application, a maximum possible increase in fatigue life of welded elements with minimum labor-and power-consumption is thought. The main functions of the developed software are:

• Determination of the maximum possible increase in fatigue life of welded elements by UIT/UP, depending on the mechanical properties of used material, the type of welded element, the parameters of cyclic loading and other factors;

• Determination of the optimum technological parameters of UIT/UP (maximum possible effect with minimum labor-and power-consumption) for every considered welded element;

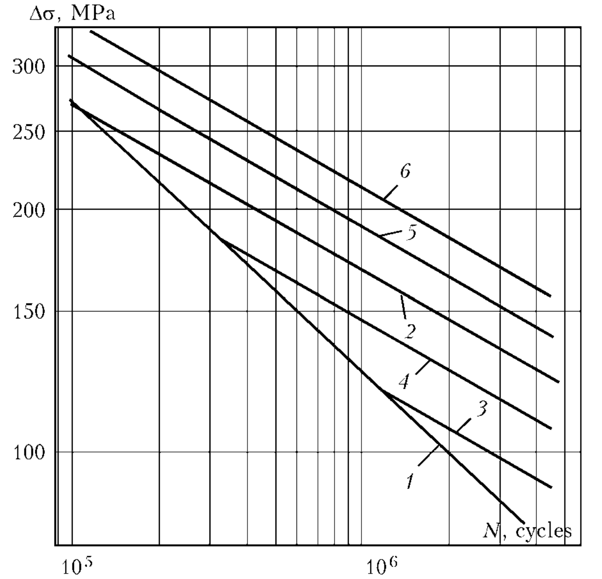

Figure 4. Fatigue curves of transverse loaded butt weld at $R = 0$: line *1* — with high tensile residual stresses; lines *2–6* — with residual stresses equals to 0, 200, 100, −100 and −200 MPa, respectively

• Quality monitoring of UIT/UP process;

• Final fatigue assessment of welded elements or structures after UIT/UP, based on detailed inspection of UIT/UP treated zones and computation.

The developed software allows to assess, through calculations, the influence of residual stress redistribution by UIT/UP on the service life of welded elements without having to perform the time-and labor-consuming fatigue tests and to compare the results of calculations with the effectiveness of other improvement treatments such as heat-treatment, vibration treatment, overloading etc.

The results of computation presented in Figure 6 show the effect of application of the UIT/UP for increasing the fatigue life of welded joints in steels of different strength. The data of fatigue testing of non-load-carrying fillet weld specimens in as-welded condition (with high tensile residual stresses) were used as initial fatigue

Figure 5. Advanced compact equipment for UIT/UP of materials, parts and welded elements

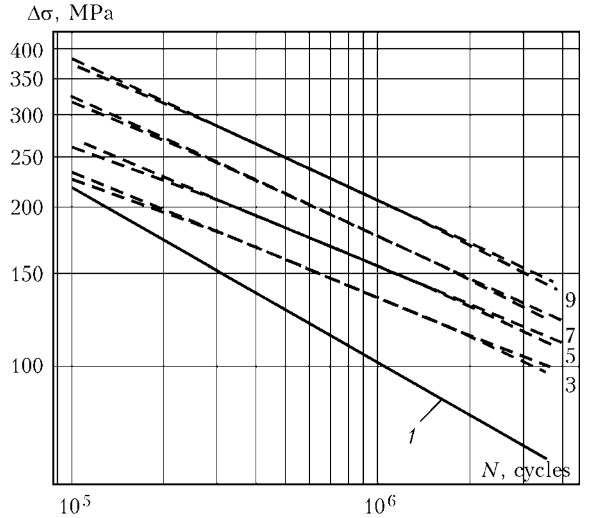

Figure 6. Fatigue curves of non-load-carrying fillet welded joint: *1* — in as-welded condition for all types of steel; *3*, *5*, *7*, *9* — after application of the UP to Steel 1, Steel 2, Steel 3, and Steel 4

data for calculating the effect of the UIT/UP. These results are in agreement with the existing statement that the fatigue strength of certain welded element in steels of different strength in as-welded condition is represented by a unique fatigue curve [1, 7]. Four types of steels were considered for fatigue analysis:

- Steel 1 — (σ_y = 270 MPa, σ_u = 410 MPa);
- Steel 2 — (σ_y = 370 MPa, σ_u = 470 MPa);
- Steel 3 — (σ_y = 615 MPa, σ_u = 747 MPa);
- Steel 4 — (σ_y = 864 MPa, σ_u = 897 MPa).

line *1* in Figure 6 is the unique fatigue curve of considered welded joint for all types of steels in as-welded condition that was determined experimentally. Lines *3*, *5*, *7* and *9* are the calculated fatigue curves for the welded joint after application of the UIT/UP for Steel 1, Steel 2, Steel 3 and Steel 4, respectively.

As can be seen from Figure 6, the higher the mechanical properties of the material, the higher is the fatigue strength of welded joints after application of the UIT/UP. The increase in the limit stress range at $N = 2\cdot10^6$ cycles under the influence of UIT/UP for welded joint in Steel 1 is 42 %, for Steel 2 — 64 %, for Steel 3 — 83 % and for Steel 4 — 112 %. These results show a strong tendency of increasing the fatigue strength of welded elements after application of UIT/UP with the increase in mechanical properties of the material used. In cases of high strength steels, the application of UIT/UP caused a two-fold increase in the limit stress range and over

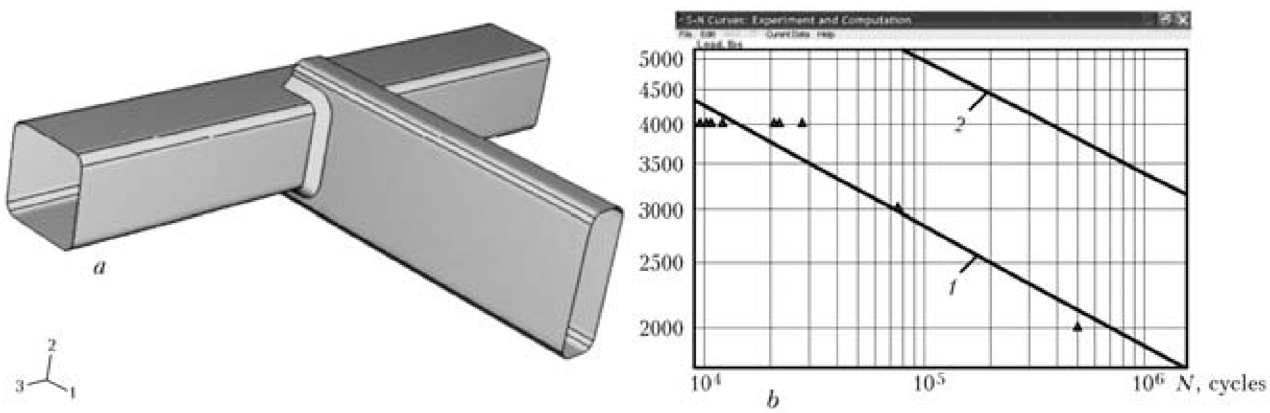

Figure 7. Fatigue curves (tendency) for tubular welded joints (as shown in the insert) showing the beneficial effect of UIT/UP: *1* — as-welded condition; *2* — after UIT/UP

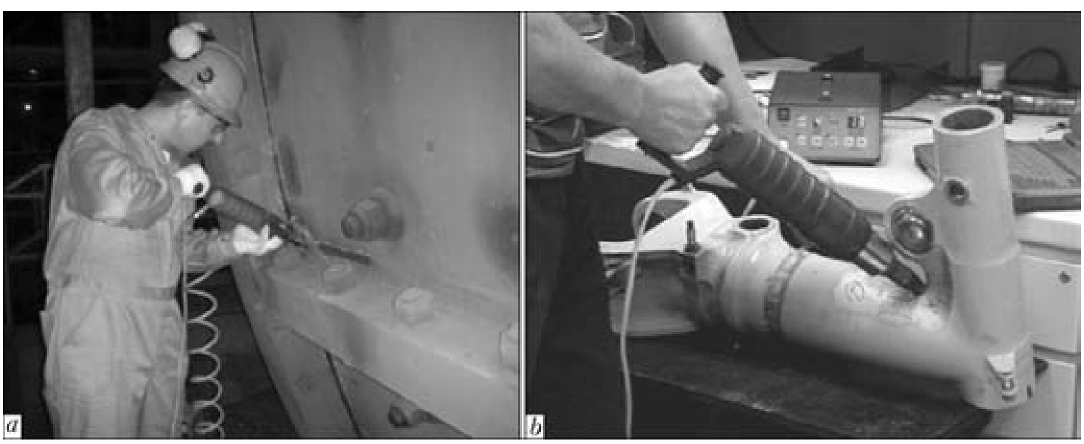

Figure 8. Examples of application of the UltraPeen system for fatigue improvement: *a* — of grinding mill when over 250 m of welds were treated; *b* — of landing gear where critical from the fatigue point of view zone was treated

10 times increase in the fatigue life of the welded elements.

As an example of application of UIT/UP, the results of fatigue testing of a tubular welded joint in as-welded condition and after UIT/UP are presented in Figure 7. As can be seen from Figure 7, in the considered case of welded T-joint of rectangular hollow section (RHS) member elements (4″ × 4″ to 2″ × 6″ welded tubes as shown in the insert of Figure 7) the UIT/UP increased the limit stress range of tubular joints by approximately 70 % and the fatigue life — by more than 10 times.

Figure 8 shows examples of industrial application of the UP system in treatment of a large grinding mill in an effort to increase the capacity of the load (Figure 8, *a*) and for redistribution of residual stresses in a critical from the fatigue point of view region of a landing gear (Figure 8, *b*).

Conclusions

1. Residual stresses play an important role in operating performance of materials, parts and structural elements. Their effect on the engineering properties of materials such as fatigue and fracture, corrosion resistance and dimensional stability can be considerable. The residual stresses, therefore, should be taken into account during design, fatigue assessment and manufacturing of parts and welded elements.

2. Certain progress has been achieved during the past few years in improvement of traditional techniques and development of new methods for residual stress measurement. A number of new engineering tools for residual stress management such as ultrasonic computerized complex for residual stress measurement, technology and equipment for ultrasonic penning and expert system for fatigue assessment and optimization of welded elements and structures were recently developed and verified for different applications.

3. The beneficial redistribution of the residual stresses is one of the efficient ways of improvement of the engineering properties of parts and structural elements. Application of the ultrasonic impact treatment causes a remarkable improvement of the fatigue strength of parts and welded elements in materials of different strength. The higher the mechanical properties of treated materials — the higher the efficiency of ultrasonic peening application. It allows using to a greater degree the advantages of the high strength material application in welded elements and structures, subjected to fatigue loading.

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Received 05.04.2013

WELDING, CUTTING AND HEAT TREATMENT OF LIVE TISSUES

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The paper presents the results of E.O. Paton Electric Welding Institute investigations and developments in the field of high-frequency welding and related technologies for joining, coagulation, cutting and heat treatment of live tissues, and also deals with the questions of development of specialized equipment and instruments for realization of the above processes. Experience of application of developed technologies and equipment in surgical practice is described, which is indicative of the high demands for them — at present more than 150 different surgical procedures have been mastered and more than 100 thous. surgical operations have been successfully performed in the most diverse surgical fields. Data are given on the features of live tissues restructuring and welded joint formation under the impact of high-frequency current passing through them. Derived experimental and clinical data were used to demonstrate the ability of tissue subjected to the impact of high-frequency welding, to maintain its viability, and restore its physiological properties and functions through regeneration processes. The paper presents the materials of studying the process of high-frequency welding of soft biological tissues with automatic regulation, ensuring guaranteed formation of welded joint in a broad range of properties of tissues being welded. Considered are the prospects for further development of technologies and equipment for high-frequency welding and heat treatment of live tissues, both due to further expansion of surgical applications, and due to development of new multifunctional apparatuses, combining the processes of high-frequency welding and convection-infrared treatment of live tissues, in particular self-sufficient mobile systems. 39 Ref., 17 Figures.

Keywords: *high-frequency welding, coagulation, cutting, hyperthermal treatment, live biological tissues, surgery, electrosurgical instruments*

In addition to the traditional application fields, such as joining and treatment of structural and functional materials, welding and related technologies are becoming ever wider applied in medicine. Therefore, utilization of capabilities provided by the new technologies of welding and treatment of various materials (in particular, biological tissues) for improvement of man's health, as well as his environment, now is one of priority avenues of research of the E.O. Paton Electric Welding Institute. At present these technologies include:

- high-frequency welding of live tissues for joining and recovery of vital functions of human and animal organs;
- hyperthermic processes of welding, cutting and treatment of live biological tissues;
- application of shape memory materials for manufacture of implants, prostheses and special surgical instruments;
- microplasma spraying of bioceramic coatings on endoprostheses;
- technology of electron beam physical vapour-phase deposition of composite nanomaterials for targeted delivery and enhancing the impact of medicines in a living organism;
- steam-plasma technologies for disposal of medical wastes.

In this paper we will describe the first two technologies and will consider the results of research and development of equipment and processes of high-frequency welding, as well as related technologies for joining, cutting, coagulation and treatment of soft biological tissues, performed at the E.O. Paton Electric Welding Institute (PWI) over the last years.

High-frequency welding of live tissues. History of electrosurgery is usually associated with discovery of thermal properties of electricity at the start of XVIIIth century, as well as Becquerel's invention of cauterodyne, the wire end of which was heated with subsequent cauterization of tissues.

The first evidence of application of high-frequency electrocoagulation equipment in medicine is associated with the names d'Arsonval, Tesla, Cushing, Bovie, dating back more than 100 years now. Apparatuses allowing destruction of tumours, removing damaged tissues, coagulating wound surfaces, etc., have been manufactured and improved for many years. At present numerous high-frequency electrosurgical apparatuses are available in the world market, which are produced by such leading manufacturers as Valleylab, a division of Covidien (USA), Ethicon, a division of Johnson&Johnson (USA), KLS Martin Group and ERBE (Germany), etc. [1–4]. Similar apparatuses are also manufactured in Ukraine, for instance, by ZAO «NII Prikladnoj elektroniki» (Kiev) [5]. However, problems of making reliable joints of live biological tissues and recovering the vital functions of human and animal organs by electrosurgery processes could only be solved in recent years with application of high-frequency welding technology. Welding of live tissues became a priority in cooperation of PWI specialists with a number of medical institutions of Ukraine, started already at the beginning of the 90ties of the previous century.

Process of high-frequency live tissue welding (HF LTW) developed at the E.O. Paton Electric Welding Institute in close cooperation with International Association «Welding», CSMG Company, USA and leading medical institutions of Ukraine, demonstrated its effectiveness and has been applied with success in medical practice for more than 10 years.

During this time more than 150 surgical procedures have been mastered and more than 100 thous. surgical operations have been successfully performed in such fields as general and abdominal surgery, traumatology, pulmonology, proctology, urology, mammology, otorhinolaryngology, gynaecology, ophthalmology, etc. In the opinion of the surgeons [6], this process is highly promising at transplantation of various organs. At present, 15 to 20 thous. operations are annually performed in Ukraine, by our estimates, using the apparatuses developed by PWI. The indisputable leader here is Donetsk Antitumour Center (headed by G.V. Bondar) [7].

Application of advanced equipment and technology is highly promising in veterinary medicine, both for surgical treatment and handling of domestic and wild animals (tumour removal, castration, etc.) and for sanitization of cities (sterilization of stray animals) [8].

HF LTW process ensures:

- bloodless, fast performance of operative interventions, convenient for the surgeon and low-traumatic for the patient, reliable hemostasis;
- lowering blood losses by more than 50 %;
- shortening operation time by 20–50 %;
- high ablasticity of operation performance;
- no suppurations;
- fast and complete postoperative rehabilitation;
- possibility of surgical treatment of patients earlier regarded as inoperable.

HF LTW advantages have been confirmed by numerous references of leading surgeons, and were noted more than once in the papers presented in conferences on live tissues welding, conducted at PWI on a regular basis [9–11].

For further intensification of work in the field of electric welding of live tissues and in keeping with the joint decision of Chief Administration of Health Care and Medical Provision of Kiev City Administration, National Academy of Sciences of Ukraine, National Academy of Medical Sciences of Ukraine and P.L. Shupik National Medical Academy of Post-Diploma Education, Kiev City Medical Training-Innovative Center of Electric Welding Surgery and New Surgical Technologies (headed by S.E. Podpryatov) [12] was established in 2011 at Kiev City Clinical Hospital No.1 [12].

Area of application of HF LTW apparatuses of PWI design (more than 150) covers practically all the regions of Ukraine, as well as some former CIS and foreign countries. Apparatuses are applied in the Russian Federation and Bulgaria, and the first batch of apparatuses was supplied to China. Such countries as USA, India, Vietnam, Poland, Macedonia, Baltic countries, etc. show interest in these developments.

Over the recent years, Western manufacturers began to use «welding» term in the list of functional capabilities of their equipment [13]. It should, however, be noted that this function pertains mainly to the procedure of vessel closing, and that Ukraine is the indubitable leader as to the number and diversity of surgical procedures with high-frequency welding application [14].

Appropriate equipment and instruments are the practical basis for realization of HF LTW process, as of any other technology. Starting with the first apparatuses, developed as far back as in the middle of the 90ties of the previous century, to date PWI has developed a wide range of specialized apparatuses [15].

At present PWI manufactures and sells EK-300M1 apparatuses of various modifications (earlier developments) and new EKVZ-300 «PATONMED» apparatus (Figure 1) [16].

All-purpose EKVZ-300 apparatus has passed clinical tests and state registration and is applied with success in surgical practice in more than 20 medical institutions of Ukraine. These apparatuses have been supplied to China for evaluation and demonstration of the new process that will be the basis for joint manufacturing of these apparatuses both for the Chinese market, and for markets of other countries.

Figure 1. All-purpose apparatus for live tissue welding EKVZ-300 («PATONMED»)

At development of EKVZ-300 apparatus, experience accumulated during operation of earlier developed equipment has been collected, and recommendations and proposals of surgeons of various specialties were taken into account as far as possible. EKVZ-300 supports operation in the following modes: cutting, coagulation and automatic welding. There is the capability of selection of various working algorithms, and working parameters of the process, depending on the kinds of operations and surgeons' requirements. Adaptation, modification and entering of additional programs can be performed by user preference. Apparatus operates in two working frequencies of 66 and 440 kHz with controlled power. Simultaneous connection of two instruments at surgeon's choice is envisaged. Apparatus is fitted with a basic set of electrosurgical instruments (pincers and forceps). Fitting with additional instruments for open and laparoscopic surgery can be performed.

This apparatus can operate with all the instruments for HF LTW, developed at PWI to date. It has been successfully tested during operation performance in various surgical fields, including general abdominal operations, pulmonology, urology, mammology, ophthalmology, etc. Operations with welding (closing) of vessels, resection of the lungs and liver, removal of kidney, intestinal anastomosis, and many other operations are performed.

Production, which allows both completely satisfying the needs of Ukraine in this type of equipment and exporting it, was set up at Science-Technology Complex (STC) «E.O. Paton Electric Welding Institute» (Figure 2).

Further development of equipment for live tissue welding, consisting of the apparatus proper (electronic module) and respective instruments with connecting cables, is associated, primarily, with improvement of the apparatuses proper, increasing their reliability, ergonomic characteristics, ease of operation and maintenance, and adaptation to surgeons' needs. At this stage, development of a new software product is required, which would be oriented to individual surgical procedures and user needs, as well as new systems of automatic control of the process. It is also necessary to develop a new specialized equipment for individual surgical fields (ophthalmology, cardiovascular surgery, neurosurgery, etc.) [15].

In addition, development of mobile systems designed for self-sufficient operation (ambulance stations, air medical service, disaster medicine, etc.) is urgently required. New EKVZ-300M (Figure 3, *a*) and EKVZ-300MDU (Figure 3, *b*) apparatuses, developed on the basis of EKVZ-300, can be the prototype of such equipment [15].

Appropriate instruments are not less important for HF LTW. To date many types of electric welding surgical instruments, mainly basic ones, have been developed and are manufactured through cooperation (Figure 4). Various type instruments for laparoscopic surgery are ever wider used (Figure 5).

In addition to basic instruments, various types of specialized instruments are applied in practice. Numerous instruments developed for the needs of otolaryngology can be mentioned as an example (Figure 6) [17].

Unfortunately, it should be noted that despite certain success, development and manufacture of new instruments of the required range and in the needed volume still do not satisfy the existing demand.

Simultaneously with equipment development, PWI, in close contact with leading medical and scientific-technical establishments of Ukraine and other countries, is performing ongoing research of behaviour of various types of live tissues at application of high-frequency currents to

Figure 2. Area for manufacturing HF LTW apparatuses at STC «E.O. Paton Electric Welding Institute»: *a* — incoming inspection and setting-up of elements and components; *b* — apparatus assembly and programming

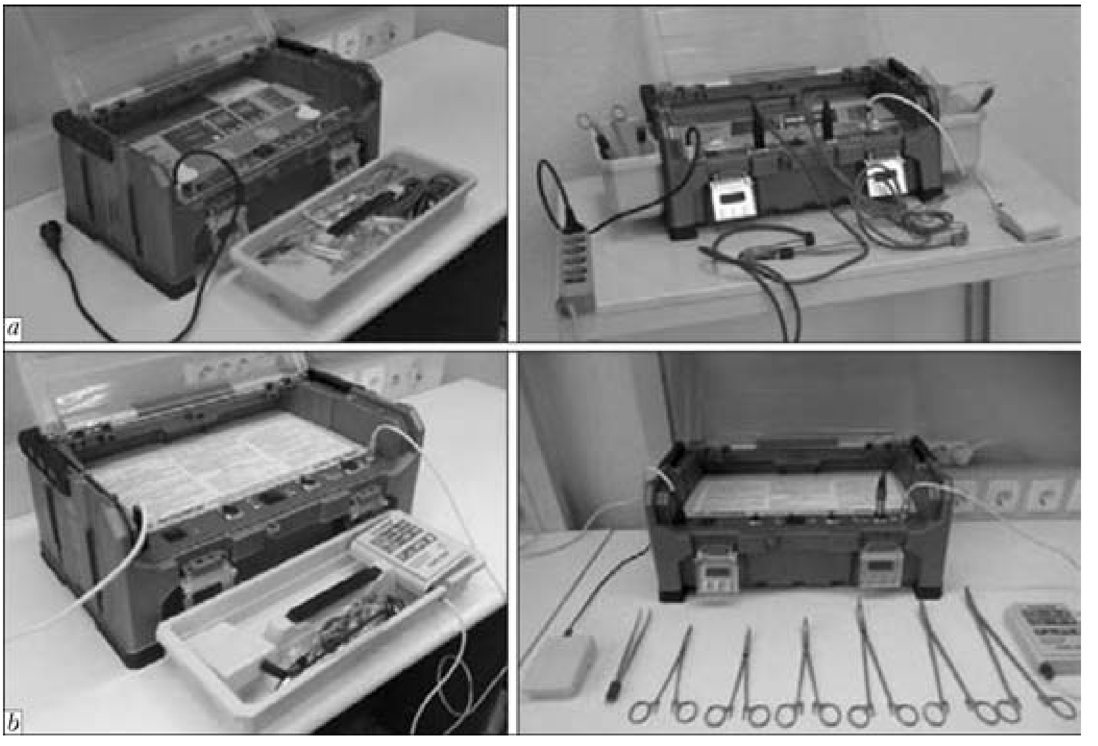

Figure 3. All-purpose mobile HF LTW apparatuses with built-in (*a*) and remote (*b*) control panel

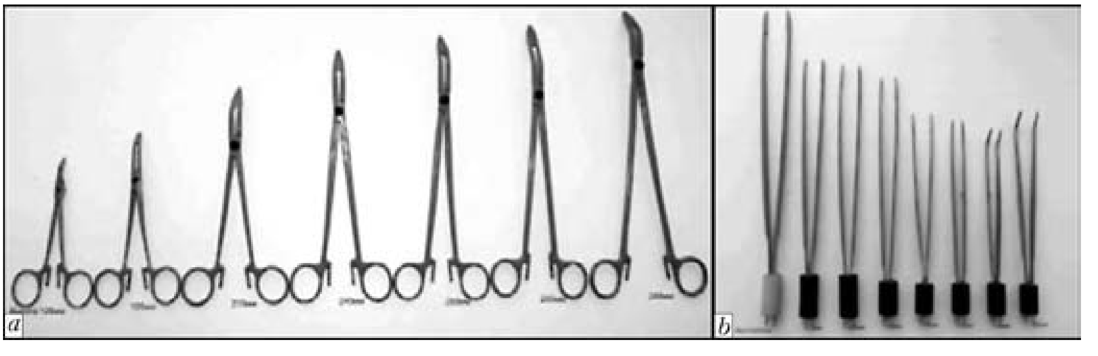

Figure 4. Basic instruments for HF LTW: bipolar electrosurgical forceps (*a*) and pincers (*b*)

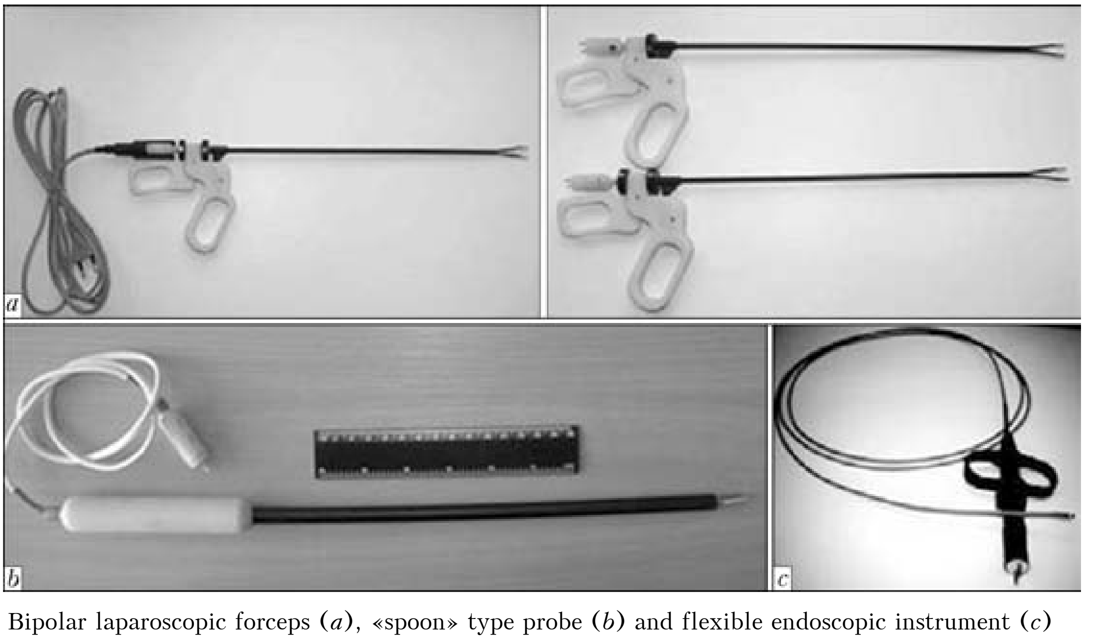

Figure 5. Bipolar laparoscopic forceps (*a*), «spoon» type probe (*b*) and flexible endoscopic instrument (*c*)

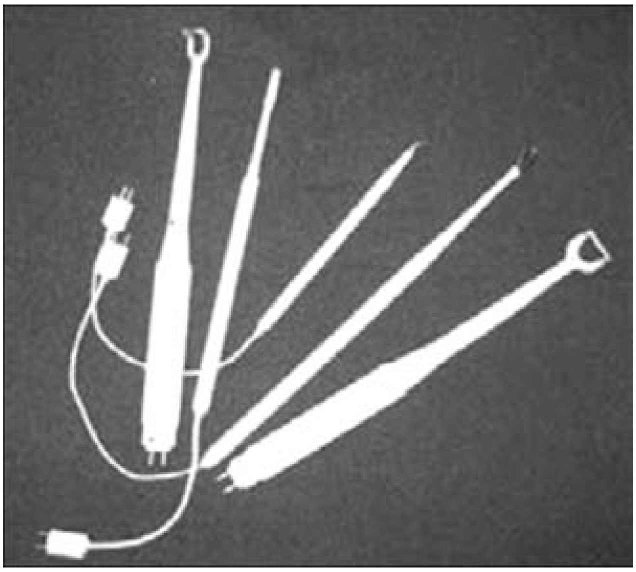

Figure 6. Instruments for HF LTW in otolaryngology

them, development of new operating algorithms for equipment on the base of research data and elaboration of new surgical procedures.

As a result of investigations conducted in cooperation with Kiev Center of Electric Welding Surgery (S.E. Podpryatov and S.G. Gichka) features of restructuring of live tissues and formation of welded joint under the impact of high-frequency current passing through them have been established for the first time [18]. The following phases of tissue restructurizing have been determined:

• separation of current-conducting structures (proteins or their complexes in the composition of collagen and muscular fibres, tissue membranes and intracellular organellas) from non-current-conducting ones (fats, glycosaminoglycans both in intertissue space and inside the cell);

• re-orientation of current-conducting structures along the current path, and of non-current-conducting ones — across the path;

• formation of fissures between current-conducting structures simultaneously with development of their undulation;

• drawing together of current-conducting structures and their coalescence with each other with formation of a homogeneous mass, which is the seam made by electric welding.

Figure 7 shows as an example, the structural changes occurring in the artery wall at its closing.

Investigation of the influence of high-frequency electrosurgical welding on the structures of various biological tissues by the method of X-ray diffraction using synchrotron radiation has been conducted in cooperation with Russian organizations: Institute of Theoretical and Experimental Biophysics of RAS and Institute of Cell Biophysics of RAS (Pushchino), as well as NITs «Kurchatov Institute» (Moscow). Derived experimental and clinical data were the basis to demonstrate the ability of the tissue exposed to the impact of HF-welding, to maintain its viability, recovering physiological properties and functions due to regeneration processes.

Operating modes of electric welding impact in the physiological range, optimized during many years of clinical practice, allowed recording the following structural changes on the molecular and nanostructural level. It is shown that in HF-welding more labile globular proteins undergo thermal denaturation: temperature increase causes structural transition of «globula-glomus» type, resulting in formation of a gluelike substance. Gluing method is widely applied in surgery. For this purpose specialized medical glues or protein preparations are used to cover the sites of joining the damaged structures, as, for instance, albumin at laser coagulation. The advantage of HF LTW (Figure 8) consists in that it is possible to avoid the presence of foreign material and problems associated with immune incompatibility.

Over the recent years PWI has conducted investigations of the process of high-frequency welding of soft biological tissues as an object of automatic regulation. Numerous experiments

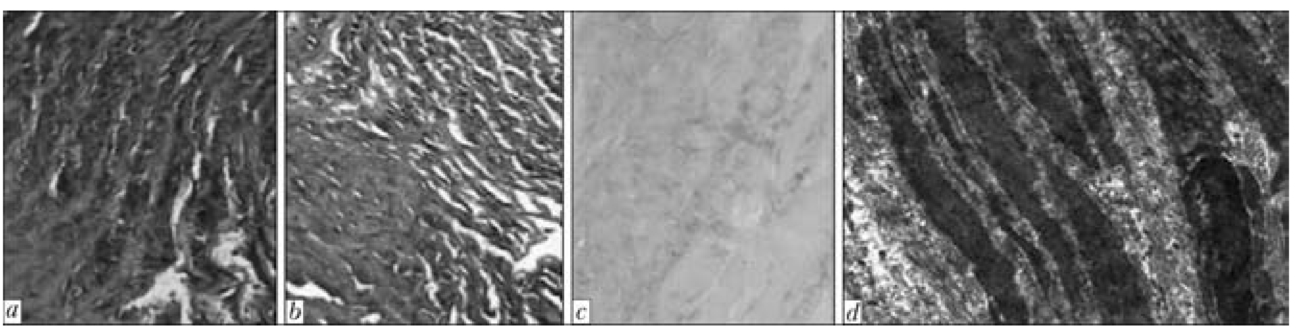

Figure 7. Structural changes occurring in artery wall at its closing: *a* — re-orientation of current-conducting structures along the direction of current passage; and of non-current-conducting ones — across current direction; *b* — formation of fissures and undulations; *c*, *d* — drawing together and coalescence of current-conducting structures with formation of a uniform mass — the welded joint

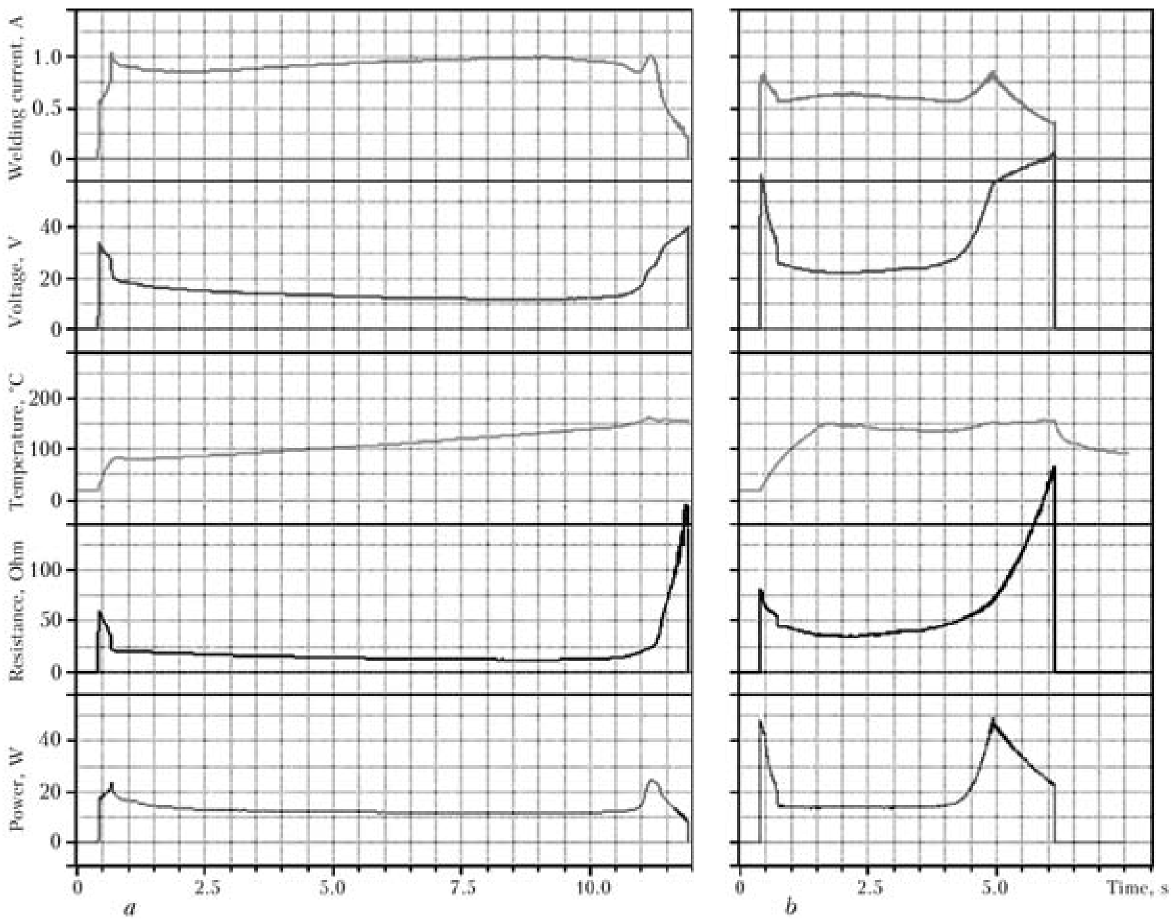

Figure 8. Oscillograms of average values of welding current and voltage, temperature in welded joint center, electrical resistance of tissue between the electrodes, power evolved in the tissue being welded: *a* — intestine; *b* — muscular tissue

were performed with recording and computer processing of electrical and physical parameters of HF LTW process. It is shown that at passage of electric current through the tissue between the electrodes, tissue temperature in welded joint center increases rapidly up to the temperature of protein coagulation and cell denaturation (60 °C), while tissue electric resistance drops 2.5–3 times. Then the temperature gradually rises up to 150–180 °C.

Tissue dehydration takes place with increase of its resistance. As a result, the fields of electric resistance, electric current and temperature become non-uniform. Current flows predominantly through sections with lower resistance at the given moment. When all the tissue between the electrodes is completely dehydrated, its integral resistance rises abruptly, that is the indication of reliably formed spot weld and signal to stop welding. Further heating will only lead to undesirable tissue carbonization.

Proceeding from the derived concepts of physical processes running in welding, a mathematical model was developed of welding soft biological tissues. Physical and the corresponding electrical parameters were determined, which characterize the end of formation of a sound welded joint. In keeping with this model, an algorithm was developed for automatic regulation of the welding process, providing guaranteed formation of a welded joint in a broad range of variation of welded tissue properties.

A fundamentally new welding apparatus was developed, which implements this algorithm. Welding mode parameters in it are set and maintained automatically by the results of identification by the system of tissue type, its state, etc. The surgeon can, at his choice, set the intensity of the welding mode — «stringent» or «soft».

These and other studies were the basis for development of new operating algorithms for live tissue welding apparatuses, one of which is schematically represented in Figure 9. Application of the proposed algorithm allows achieving an optimum impact of HF current on the tissue being operated on, that eventually enables making a high-quality joint [20]. Specific parameters are assigned proceeding from specific conditions of performance of surgical interventions.

The following can be noted as a concrete result of application of new operating algorithms. Closing of up to 8 mm arteries and up to 11 mm veins

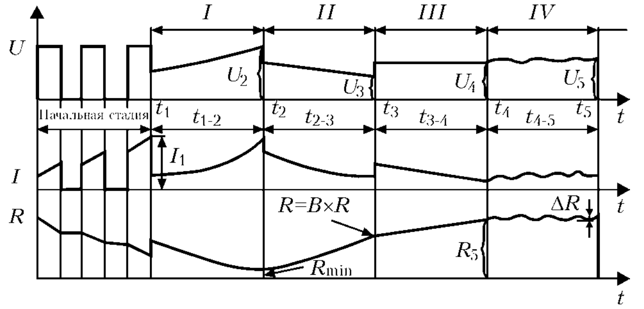

Figure 9. Typical algorithm of live tissue welding [20]

was achieved in the clinic in cooperation with the doctors of Kiev Center of Electric Welding Surgery using standard apparatus EKVZ-300 («PATONMED») and instruments [12]. Formation of the liver parenchyma seam by electric welding has been achieved for the first time. Positive results have been obtained in surgical treatment of pancreatic diabetes with application of the technology of welding live tissues in open and laparoscopic variants. New technology of retropubic prostatectomy has been verified and is applied with success in surgical treatment of prostate adenoma [21]. This technology has a number of advantages compared to the currently available one that allows characterizing it as one of the most promising in treatment of this rather wide-spread disease.

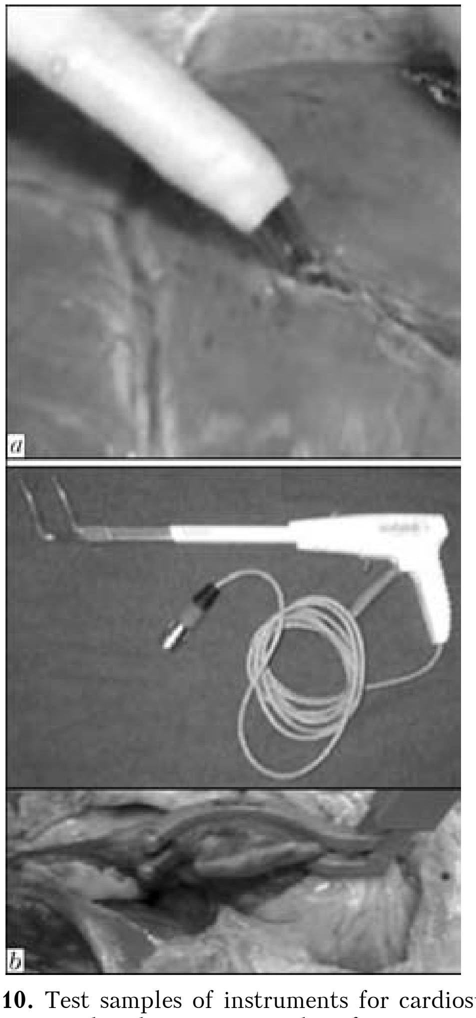

Figure 10. Test samples of instruments for cardiosurgical operations: *a* — bipolar HF-cauterodyne for operations with simultaneous tissue cutting and coagulation; *b* — bipolar forceps for transmural ablation of heart conduction tracts

Application of high-frequency electric welding in cardiosurgery seems to be promising. To widen the range of HF-welding applications in the above-mentioned surgical field and develop respective equipment, the Interbranch Center of «Cardiovascular Engineering» was established, uniting specialists of the E.O. Paton Electric Welding Institute of NASU, N.M. Amosov National Institute of Cardio-Vascular Surgery (NISSKh) and National Technical University of Ukraine «Kiev Polytechnic Institute».

This center performs development of specialized apparatuses, instruments and technologies: cardiosurgical instruments for transmural ablation of heart conduction tracts, diothermocoagulation of tissues and hemostasis, instruments for conducting cardiosurgical operations with simultaneous cutting and coagulation, etc. [22]. Test samples of the above instruments have been developed, which have successfully passed preliminary trials (Figure 10) [23].

It is planned to perform work on further improvement of apparatuses and instruments, in keeping with vascular surgery specifics, as well as develop and introduce new procedures of operational interventions at N.M. Amosov NISSKh and other cardiosurgical institutions of Ukraine.

Work on welding live tissues in ophthalmology, conducted together with specialists of V.P. Filatov Institute of Eye Diseases and Tissue Therapy of AMSU (Odessa), should be mentioned separately. So, jointly developed technology of retina welding is one of the most effective procedures at present. To date HF-electric welding is quite widely applied in ophthalmosurgical practice of the above-mentioned Institute [24–26].

In particular, HF LTW is applied during enucleation (eyeball removal) in patients with intraocular neoplasms, malignant secondary neovascular glaucoma, etc. Excision of eyeball rectus muscles from sclera, and crossing of neurovascular bundle are performed in «Cutting» mode, and adaptation of conjuctival cut edges is conducted in «Welding» mode.

In retinal and vitreous surgery electric welding is applied in patients with retina detachment, diabetic retinopathy (one of the gravest complications of pancreatic diabetes) and intraocular neoplasms.

Operations are performed using original parameters of PWI-designed apparatuses modified for ophthalmology and jointly developed original instruments (Figure 11).

In addition, experimental research is performed in the following directions:

• devitalizing malignant choroid neoplasms. The new method will allow increasing the effectiveness of treatment of patients with malignant intraocular neoplasms through improvement of ablastics quality;

• trabeculectomy. Electric welding will allow improving the effectiveness of treatment of patients with secondary neovascular glaucoma through improvement of hemostasis quality at trabecule crossing;

• retinal surgery (layer-by-layer keratoplasty). HF LTW will allow improvement of the quality of layer-by-layer keratoplasty due to seamless fixing of retinal transplant.

At the same time, PWI has successfully performed and continues work in other directions of application of HF LTW and related technologies in medicine. They include methods of contactless thermosurgery. Let us present this work in greater detail.

Hyperthermic processes of welding, cutting and treatment of live tissues. In 2001 DB «Yuzhnoje» and PWI jointly developed plasma-surgery complex «Plasmamed» [27]. This marked the beginning of development of a new medical field in Ukraine: contactless hyperthermic surgery.

At the first stage an apparatus was developed, which performs cutting of parenchymatous tissues and stopping intrawound bleeding by a jet of low-temperature argon plasma. This apparatus received positive medico-technical evaluation and a procedure of plasma welding of live tissues of the intestines and stomach was developed, as well as the method of joining the parenchymatous wound edges.

As a follow-up of these investigations PWI in cooperation with A.A. Shalimov National Institute of Surgery and Transplantology developed a procedure and apparatus for convection-infrared (CI) treatment and welding of live tissues. This process features simplicity and ease of application of apparatuses developed for it, as well as use of ambient air instead of argon. Novelty of the developments is confirmed by Ukrainian patents [28–31]. This process provides reliable hemostasis, ability to form coagulated blood films on tissue surface, absence of thermal injury of organ parenchyma, possibility of safe operation in the vicinity of great vessels and hollow organs (Figure 12).

Checking of the main design and program solutions of these apparatuses has been performed.

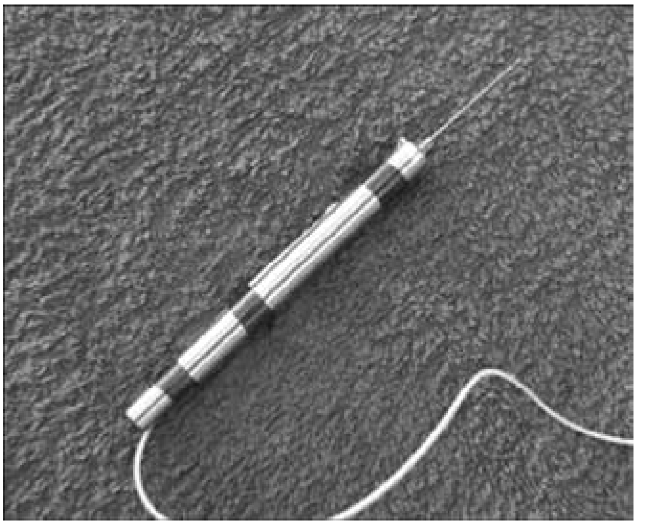

Figure 11. Instruments for HF-welding in ophthalmology

Test samples of apparatuses for CI-treatment of live tissues and instruments for them have been developed and tested. A line of apparatuses has been created for field applications: full-scale TPB-65, budget TPB-65B, automobile TPB-65Aut, wireless TPB-65Ak (Figure 13). The following apparatuses have been developed for stationary operating rooms: full-scale TPB-180, full-scale TPB-180^{UPS} with built-in UPS unit, and budget TPB-180B (Figure 14).

Most of the apparatuses can operate in self-sufficient mode and use car power system, field electric power stations as power sources, and TPB-200HF apparatus can also fulfill the manipulations of high-frequency cutting and coagulation of live tissues.

Preclinical studies of CI-apparatuses and their application procedures have been performed at A.A. Shalimov National Institute of Surgery and Transplantology with participation of specialists

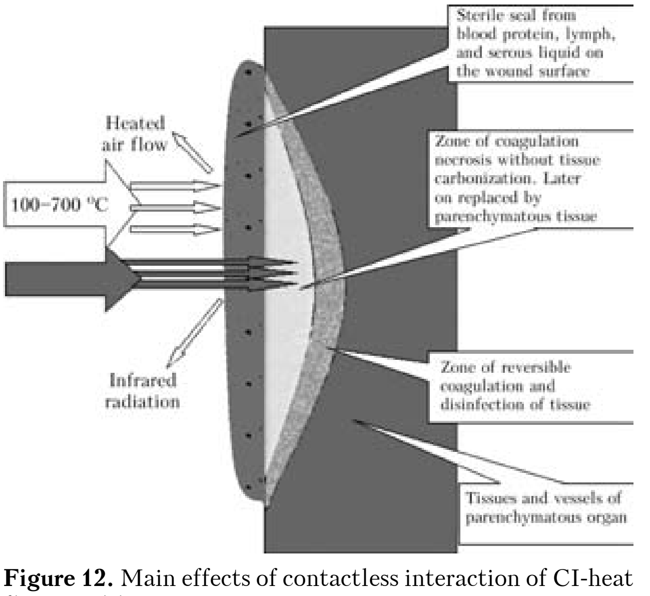

Figure 12. Main effects of contactless interaction of CI-heat flows and live tissues

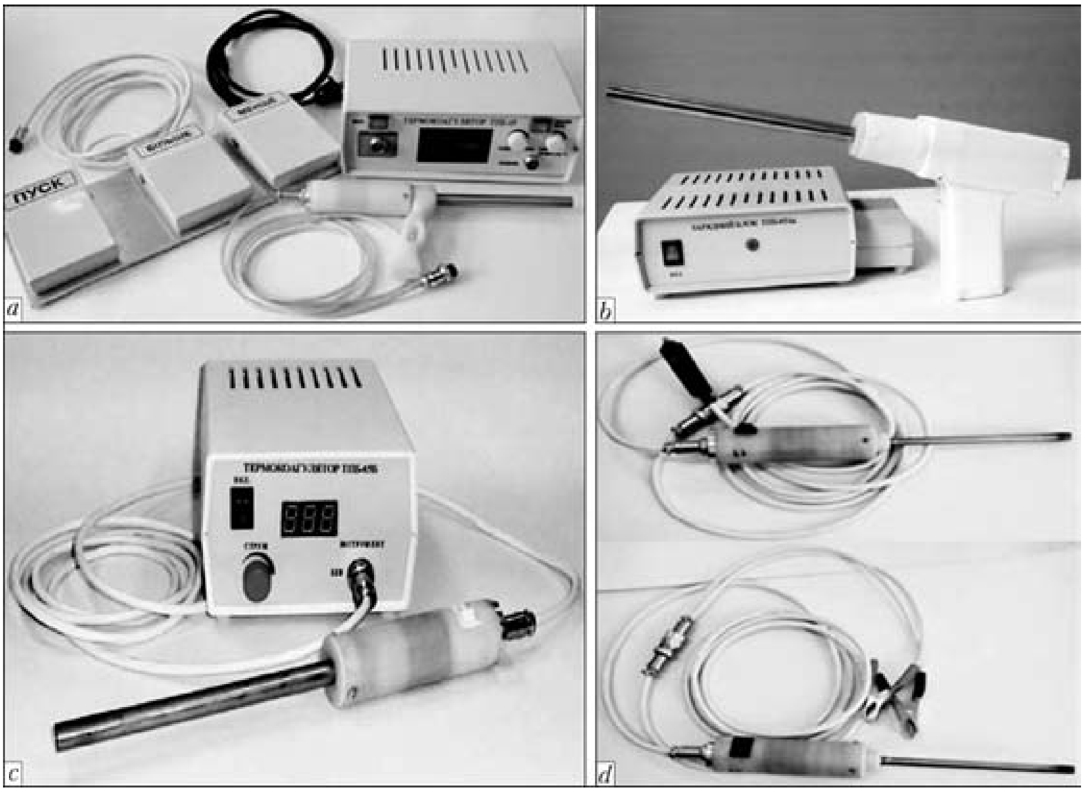

Figure 13. Apparatuses for CI-treatment of live tissues: *a* — TPB-65; *b* — TPB-65Ak; *c* — TPB-65B; TPB-65Aut

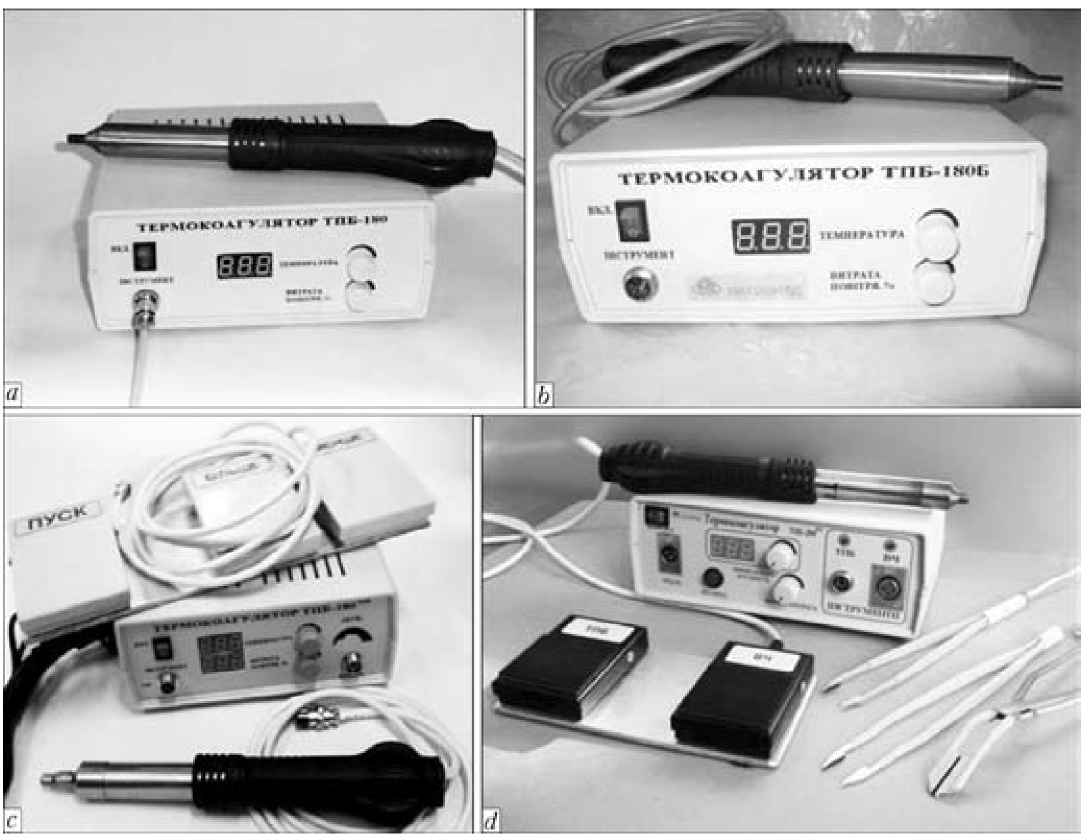

Figure 14. Apparatuses for CI-treatment of live tissues for stationary operating rooms: *a* — TPB-180; *b* — TPB-180B; *c* — TPB-180^{UPS}; *d* — TPB-200VCh

of Ukrainian Military-Medical Academy and surgeons of Main Hospital No.1 of GTOO YuZZhD.

Investigations in the field of CI-treatment of live tissues in surgery demonstrated the good prospects for this method, particularly under the conditions of surgical interventions complicated by infections. This method was modified for stopping bleeding and prophylaxis of infection development in gunshot wounds (Figure 15) [32].

High effectiveness of the method was established, irrespective of specific apparatus realization, at stopping bleeding from up to 3 mm vessels, at bleeding from damaged parenchymatous organs, trabecular bones, d-bridement of infected and chronic purulent wounds [33, 34].

A mixture of antibiotic-resistant microorganism cultures (clinical strains) consisting of colon bacillus, pneumonia klebsiella, blue pus bacillus, golden stafilococus, enterococus faecium, candida fungus, was used as infecting material in tests on laboratory animals (rats, rabbits, pigs). CI-method of wound treatment has successfully passed preclinical tests and, in the opinion of many leading surgeons, its wide introduction into surgical practice is rational. At present more than 200 operative interventions have been performed with application of the method of CI-treatment of wounds and stopping parenchymatous bleeding.

Such apparatuses can be used for rendering first aid to victims of accidents and catastrophies both in the field conditions in immediate vicinity of injury site and in hospitals. CI-apparatuses essentially improve the effectiveness of specialized and highly specialized surgical aid, particularly at polytraumas and surgical interventions complicated by infections [35, 36]. CI-technology allows stopping bleeding from parenchymatous organs, trabecular bones and vessels of 1–3 mm diameter, d-bridement of infected and chronic purulent wounds, profylaxis of purulent infection at combat injuries, welding of tissues of gastro-intestinal tract organs, tissue coagulation for performing bloodless dissection, and profylaxis of relapses and metastasis development at tumour removal (Figure 16).

Alongside the above-mentioned applications of CI-method of welding and treatment of live tissues, development of hyperthermic method for destroying malignant tumours and metastases was begun, which is an urgent and promising direction of research.

Development of multifunctional apparatuses, combining the processes of high-frequency welding and CI-treatment of live tissues, is one of the important tasks in creation and introduction of new generation of electrothermosurgical equipment. First model samples of such equipment based on EK-300M1 (Figure 17) are now passing comprehensive clinical trials. Model samples of CI-instruments for EKVZ-300 «PATONMED» apparatuses have been developed. Thus, in the future most high-frequency apparatuses for live tissue welding will have the functions of CI-treatment of tissues. In the opinion of surgeons, combination of the above processes in one multifunctional apparatus allows performing up to 80 % of standard surgical manipulations with it [37, 38].

Figure 15. Surgical treatment of infected gunshot wound by CI-flow

An independent highly promising direction of PWI activities is development of complex medical technologies aimed at solving some medical problems, such as reconstructive-restorative surgery, cardio-vascular surgery, and ophthalmology [39]. Solution of these problems requires involvement of specialists from various fields, departments and even other institutes.

Problem of reconstructive-restorative surgery covers materials, technologies, apparatuses, sur-

Figure 16. Stopping bleeding with CI-coagulator and d-bridement of an infected wound after amputation of finger bone

Figure 17. Multifunctional apparatuses for high-frequency welding and CI-treatment of live tissues, based on EK-300M1

gical procedures, used in orthopedics, traumatology, oral surgery, and stomatology to increase the effectiveness of operative interventions and shorten the periods of recovery of intactness and functions of support-motor apparatus. Individual directions also deal with prosthetics, oncology, neurosurgery and vertebrology (as regards restoration of integrity of bones, intervertebral disks, ensuring spine mobility).

For instance, during operative intervention for open fractures, high-frequency welding of live tissues is used to obtain operative approach, stopping bleeding from great vessels and welding individual elements of live tissues. D-bridement of an initially infected wound and stopping bleeding from trabecular bones are performed by CI-coagulator. Titanium composites, elements from bioactive ceramics — biosital, hydroxyapatites, β-tricalciumphosphate are used for osteosynthesis. They form a bone-ceramic block, which is gradually replaced by sound bone. Special technologies of filling bone defects with hydroxyapatites with osteoconductive and osteoinductive additives, produced using nanotechnologies, allow a significant acceleration of the process of bone restoration in the fracture zone.

Complex application of thermosurgical technologies and new materials for osteosynthesis and prosthetics allows conducting single-stage reconstructive operations without removal of osteosynthesis elements after bone restoration.

The above advantages and merits of the new processes of welding, cutting and heat treatment of live biological tissues allow anticipating their wide application. In the future, in the authors' opinion, apparatuses for high-frequency welding and CI-treatment of live tissues should become an invariable attribute of each operating room and each operating table.

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RECRUITING AND PREPARING SKILLED PERSONNEL FOR LEADERSHIP ROLES IN WELDING AND BRAZING

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A shortage of welders and welding professionals is felt globally, and it will worsen as the current skilled and educated leave the workforce. Thus, many countries are actively designing programs to improve the image of welding and to train and educate persons to meet those needs. Virtual welding, by means of computer simulation, is one method of introducing and exciting the young about welding. Some companies are even using the virtual welder as to test or even give basic training to new employees. Females are 50 % of the population, yet too few choose welding. We have good role models in the many different areas of welding and they are highlighted here. Once persons are interested in welding, they need to be properly trained and educated. Weld-Ed is a program in the USA that has: a model curriculum for 2-year colleges; a program to update and upgrade instructors; a method of pairing industry with schools and colleges to offer necessary skills and knowledge for available jobs. New technology is being used by several countries in a variety of ways to enhance training and education. Several types, including online learning and electronic devices, will be described. As persons become skilled and educated, they need a way to prove their competence. A cost-effective means of demonstrating their competence is a Certification Program. Bright young persons are needed in welding science and technology to meet national and global challenges. Our future, structures, and infrastructure depend on them. 2 Ref., 17 Figures.

Keywords: *educating, computer simulation, virtual welding, Weld-Ed program, Certification Programs*

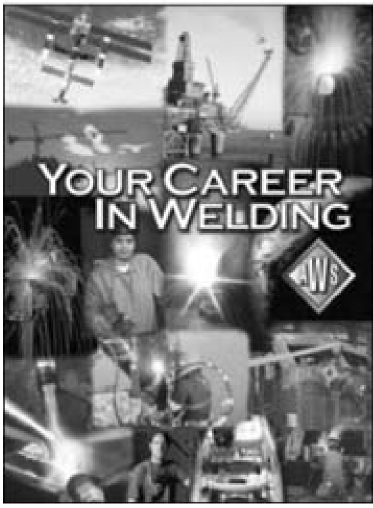
At present, there is a worldwide shortage of welders and welding professionals. Persons around the world emphasize that we need to attract and train more persons to enter and contribute to welding and brazing. Of the half-million or so welders presently working in the United States, the average age is in the upper 50 s, and some 50,000 of these skilled craftspeople retire each year. At the same time, there is a growing need for professional welding personnel in national infrastructure, energy production, petrochemical and many other industries. If this need is not met, the U.S. welder shortage could reach a quarter million by 2019.

However, the need is for skilled and educated welding professionals. Since 2009, the unemployment rate has risen dramatically in the United States. Data from the Bureau of Labor and Statistics indicate that this spike in unemployment has disproportionately affected «blue collar» workers. Yet, the high unemployment rate affecting the manufacturing industry is inconsistent with manufacturing job market. While the manufacturing industry is experiencing high unemployment rates, it also reports a large number of unfilled, high-paying jobs. This separation between the larger numbers of unemployed workers and open positions can be attributed to the «skill gap» existing in the workforce. This «skill gap» is formed by the separation between the skill or knowledge base needed to compete in the global marketplace and the skill or knowledge base currently held by the workforce.

A skills gap study looked for a means of determining the nature of the skill and talent gap in the manufacturing industry in the United States [1]. The survey was answered by more than 1,100 executives from all fifty states in the USA. The Skill Gap Report indicated that 67 % of manufacturers in the United States describe a moderate to severe shortage of «available, qualified workers». In addition, the survey indicates that 5 % of current jobs (approximately 600,000 jobs) at responding manufacturers are unfilled due to a lack of qualified workers.

This skill gap is further complicated by the necessary evolution occurring in the welding industry. The American Welding Society's Vision for Welding Industry report states: «Until recently, welding itself was a skill that craft people could learn without a real understanding of the science behind it. The scientific and engineering principles behind welding must replace the art of welding for it to achieve its potential as a preferred state-of-the-art manufacturing process [2]».

Thus we have a need, but we must attract persons to the field by effective means, and we also must overcome a pervasive incorrect image and then provide the necessary training and education.



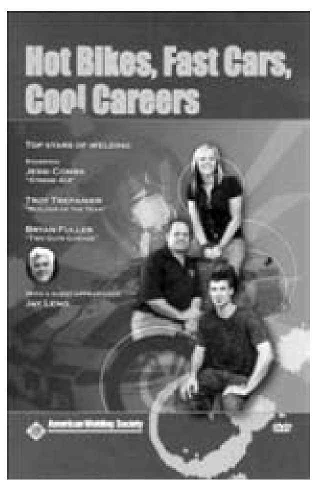
Career In Welding Brochure Ironman Comic Book Cover Ironman Comic Book Inside Page

Attracting persons to the welding and brazing profession. *Welding offers numerous and varied job opportunities*. The skilled worker problem is exacerbated by the fact that welding has long had an image problem. Many students, parents and guidance counselors hold an out-of-date perception of welding as an unpleasant and dangerous occupation suitable only for those who cannot, or do not wish to, pursue university educations. In fact, welding as a profession offers many opportunities at all levels of employment in energy, defense, manufacturing, construction, aerospace, shipbuilding, utilities, repair, environmental applications — in short, wherever metals are permanently joined. Job opportunities start with the welder, but also include engineer, inspector, educator, researcher, business owner, equipment sales, computer programming and more. Workplace environments include manufacturing facilities and construction sites in just about every industry imaginable. And, potential income is high, often significantly higher than that achieved by university graduates in other fields. The average starting salary for graduates of the Tulsa Welding School in Jacksonville, Florida, is $ 42,800 (32,400 EUR) and it increases rapidly as new skills are developed. Pipeliners on Alaska's North Slope oil fields have earned as much as $ 1000USD (757 EUR) a day.

Spreading the word through print publications and videos. One of the first steps taken by AWS was publishing a guide to available careers in welding, as well as establishing a Web site devoted to explaining employment opportunities in the field. This was followed by a special edition of an Iron Man comic book commissioned by AWS with the Marvel Comics Group. Aimed at a younger audience (9–15 years of age), the comic used the action hero's print medium to tell a story of career opportunities in welding.

This was followed by establishing links with several television personalities in the United States starring in reality shows that feature welding. These included Troy Trepanier, named hot rod «Builder of the Year»; Brian Fuller, of «Two Guys Garage»; and female welder Jessi Combs of «Extreme 4X4». AWS also visited well-known television talk show host and automobile collector Jay Leno, who recorded a video segment testifying to the importance of welding and the well-paying job opportunities in the field. AWS then produced a DVD — «Hot Bikes, Fast Cars, Cool Careers» — featuring all four personalities and distributed thousands of copies through schools, trade shows, career days, and the society's 160 member Sections throughout North America. Of course, the entire contents of the video were also posted on the AWS Web site.

For those individuals who gained a basic interest in welding, AWS established a Welding School Locator on its Web site that lists thou-



AWS Produced DVD

sands of schools across the country that can provide quality welding education. The Society also launched a separate Web site, www.jobsinwelding.com that brought together trained welding personnel and potential employers. That valuable tool contains over 88 % of the welding jobs posted anywhere on the internet.

Publicity through outside media. AWS has also successfully sought media publicity about the shortfall of needed welding personnel. This has resulted in major stories on the subject in the New York Times, U.S.A. Today, Atlantic Monthly and many other publications. Television and radio networks have also broadcast stories on the need for welding workforce development. One of the most widely heard of these was a radio interview with AWS Marketing/Communications Director Ross Hancock on the BBC World News.

The careers in welding road show. Another method of putting the word out about welding careers was to plan a road tour where interested parties could actually get the feel of welding. Through the inspiration of 2012 AWS President William Rice, and with a large donation from The Lincoln Electric Company, AWS designed and built a 53-ft (16 m), over-the-road tractor trailer with over 650 sq.ft. (60 sq.m.) of exhibit space to travel throughout the U.S. and Canada promoting career opportunities in welding.

AWS trailer containing virtual welders and welding exhibits

Lincoln Electric donated five VRTEX 360 virtual welding simulators to give trailer visitors a realistic sense of the welding experience. The simulators also provide a score for each person using them to help measure aptitude for the profession. The trailer was previewed in late 2011 at the Future Farmers of America National Convention, where it attracted more than 5,000 young people interested in welding. It has since been featured twice at the FABTECH show in the U.S., at FABTECH Canada, at several State Fairs, at the Indianapolis 500 auto race, and at other specialty events with a focus on welding. It reached over 35,000 individuals in its first year and is designed to excite young people about the many career opportunities available in the welding industry.

Image of welding awards. Yet another important step AWS has undertaken to improve the public perception of welding is establishing the annual Image of Welding Awards. These prestigious awards are presented each year at the FABTECH show to honor individuals, companies and AWS Sections that have shown outstanding achievement in promoting welding careers and creating a positive image for the profession. The awards include presentation of a handsome trophy, and the winners receive media recognition in numerous trade publications and local media.

Boy Scouts of America Welding Merit Badge. To further interest youth in welding careers, AWS has worked with the Boy Scouts of America (BSA) in establishing a Welding Merit Badge, officially launched in 2012. Boy Scouts earn the badge by studying welding technique and completing a welding project. To help them prepare, many AWS volunteers actively work to train and counsel the scouts attempting to earn the badge.

Boy Scouts of America Welding Merit Badge

Social media involvement. A recent effort by AWS to publicize welding careers has been to become strongly involved in Facebook, Twitter and other social media. AWS has launched a Facebook page that actively promotes careers in welding. The Society has also hired a permanent staff expert in social media.

Women in welding and brazing. The above efforts target the general population worldwide and youth in particular. However we need to target another specific audience. Women make up about 50 % of the population at large, but their percentage in welding and brazing is much lower. In fact in the USA, the Department of Labor estimates that women in welding make up no more than 6 % and female welders are probably no more than 2 %. That population provides a great opportunity to increase the numbers of

Welder Callie Jones-Hughes

Welder Melissa Hall

welding professionals. In the USA during World War II, women stepped into the workforce to meet the country's need. Rosie the Riveter was advertised, but there was also Wendy the Welder and Barbara the Brazer. Women can do it again and in fact we have plenty of female role models, we just have to let them be known. Below are several women who are effective role models.

Callie Jones Hughes is a welder at P&H Mine Pro in Wyoming. She has a family history of welders. Her great grandmother welded during World War II, and her grandfather on the other side of her family welded in a shipyard. She says, «I would love to inspire other women to be welders. I think it is very neat that I had past family members who were welders on both sides».

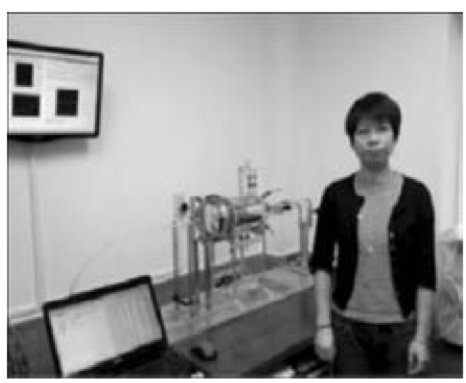
Trainer Chris Monroe

CWI Nan Samanich

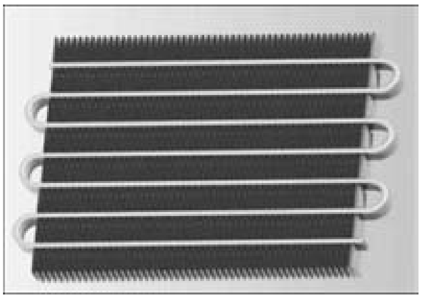
Welding Engineer Pierrette Gorman

Another welder is Melissa Hall, who has been welding since the 9th grade. She has an Associate Degree in Welding and Fabrication from Triangle Tech in Sunbury, Pennsylvania, and is a member of Local 520 of the Plumbers and Pipefitters Union. She does welding for nuclear and shale gas companies.

Materials Engineer Robin Gourley



Brazing Engineer Hui Zhao



MicrochanneL Heat Exchanger (enlarged)

Welding Sales Claudia Bottenfield

Chris Monroe is a welding trainer at Hobart Brothers, Troy, Ohio. She sums up the opportunity well: «There's an opportunity in this industry to have a career for life. You can work on the manufacturing floor or in the field as a welder, or as an ironworker building a stadium. You can become an engineer and develop welding products or travel around the country as a Certified Welding Inspector».

Other role models are members of AWS Board of Directors. Nan Samanich is District Director 21 and is an AWS Certified Welding Inspector (CWI) and Welding & Metals Technology Instructor at Desert Rose High School and Career Center, Las Vegas, Nevada. 2014 Incoming District 20 Director, Pierrette Gorman, has a B.S. in Welding Engineering Degree from The Ohio State University (OSU), Columbus, Ohio, and she's a laser and soldering specialist at Sandia National Lab, Albuquerque, New Mexico. She went to OSU at the age of 40 to get that degree.

Robin Gourley is a Materials Engineer at Curtiss-Wright, Cheswick, Pennsylvania. She's responsible for metal brazing processes of pumps and motors for commercial and naval products. She has been an active member of the AWS Brazing and Soldering Committee for over 15 years and has presented papers and been responsible for helping organize the successful International Brazing and Soldering Conference for many years. She also writes for the Brazing Handbooks.

Hui Zhao of Creative Thermal Solutions, Urbana, Illinois, is one of the few females who has a PhD and is working in the joining field. Her undergraduate work was in China and she earned her PhD in Mechanical Engineering at the University of Kentucky. She is pictured in front of her lab furnace where she is able to observe the brazing of micro channel heat exchangers. An enlargement of the heat exchanger is also shown.

Deanna Postlethwaite of Lincoln Electric Co., Cleveland, Ohio, is in Technical Marketing. She says, «I am enjoying the opportunity to provide solutions to companies to keep productive manufacturing in the USA. I am also actively involved in the development and marketing for our virtual reality welding solution».

Claudia Bottenfield, former AWS District Director from Maryland was a single mother raising two sons and welding sales provided the income she needed. She says, «Four years after starting at Arc Welders, I was asked if I wanted to sell our products to end users. I jumped at the possibility since I would be the first woman in the Baltimore area to ever have accomplished this feat».

Karen M. Gilgenbach has many credentials, CWI, CWS, CRAW-T, WTC-WI, B.S. Engineer. She is also a Weld Process Specialist with Airgas, Inc., and the Past Chair, AWS Milwaukee Section. She is also known as a very good welder.

These women are only a few of the female role models working in welding and brazing, so we do have role models who are leading the way. However, because their percentage is currently small, females need to be encouraged in all possible ways. They need mentors and need to be given opportunities.

The general public needs to know that welding and brazing is a great field for both men and

Tech marketer Deanna Postlethwaite

Karen Gilgenbach with other AWS members

women with many opportunities in a variety of occupations. Hopefully, in the future we will see more instances like the welding class in Floresville High School with a ratio closer to the world's population of 50/50 of women to men.

Obtaining National Science Foundation Funding. In 2007, AWS teamed with Ohio State University, Lorain County (Ohio) Community College and other educational institutions and created the National Center for Welding Education and Training (Weld-Ed) using a financial grant from the National Science Foundation. Operational partners for Weld-Ed include AWS through its Foundation, Lockheed Martin, The Lincoln Electric Co., and a number of schools — all committed to increasing the number and quality of welding and materials joining technicians to meet industry demands. In addition, Weld-Ed's network has grown to include over eighty education and industry affiliates who participate in the Center's programming and utilize its resources.

One important result of this partnership was a joint AWS/Weld-Ed publication designed to promote careers in welding. Titled «In Demand — Careers in Welding», the magazine contains articles promoting welding as a dynamic field with a strong future, personnel profiles with realistic salary figures, technical facts about welding, and more. So far, more than 50,000 copies of the magazine have been distributed, and an on-line version www.careersinwelding.com, has proven equally popular. The site contains useful information for students, parents, educators, and counselors, as well as welding professionals.

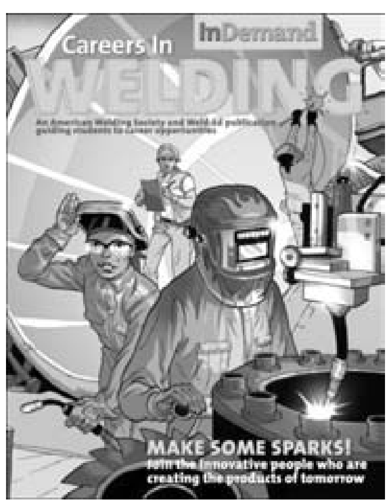
Providing proper training and education. Attracting persons to the welding profession is not enough. It's the skilled and educated welding professional that is in high demand. Therefore, several means of delivering the necessary skills and education have been devised locally and internationally. Canada has a case study of a modern welding education facility that uses technology to enable multiple students to see the instructor and activity clearly and is used to illustrate a variety of application technologies. The IIW has designed a system that ensures that qualified students can be admitted to welding training and education courses in a wide range of personnel categories. These students benefit by taking courses that are harmonized across national boundaries and their diplomas can be recognized as equivalent. This system has proven advantages in closely related economies such as the European Union. Sweden has adopted that method and now has welding as a specialization that is available in upper secondary schools. Sweden is considered to be a role model for that method of providing a welding education.

In the USA, we are pursuing other models. Schools, colleges and universities teach welding in the traditional way in a classroom and lab setting, but their curriculum may vary depending on the school and location. We tend to measure outcomes — the skills the student has obtained and what has he/she learned, which is the basis of the certification programs, rather than where the person received their training. However, different means of providing the skills and education are being developed.

Weld-Ed. Weld-Ed strives to improve the quality of education and training services to address the hiring and professional development needs of the welding industry. Weld-Ed has three overarching goals that drive its activities.

• Increase the number of welding technicians to meet workforce needs. This goal is accomplished in partnership with the American Welding Society and involves several initiatives. The first is the development and distribution of recruiting materials for middle school, high school, and college age students, covered above. Additional, very successful resources have been developed, including a DVD — Improving their Competitive Edge: Students in Welding. AWS and Weld-Ed also collaborated on a resource for secondary educators to use in their math and science classrooms. Engineering Your Future explores the ever-increasing relationships among

Welding Class at Floresville High School, South Carolina



In Demand — Careers in Welding Publication science, technology, and society. The goal of the program is to excite students about some of the natural laws of physics and their application in the technological world in which we live, while perhaps guiding them to consider science-based careers. In the first six months since its introduction, over 4,900 free copies were distributed.

- The second initiative involves disseminating the message that careers in welding are abundant, highly skilled, and utilize advanced technology. The Careers in Welding trailer, described earlier, reached over 35,000 individuals in its first year. This mobile exhibit features the five arc welding simulators as well as interactive exhibits designed to excite young people about the many career opportunities available in the welding industry.
- The third initiative includes research on welding industry trends. In 2010, Weld-Ed released The State of the Welding Industry report, a comprehensive examination of the welding industry, including industry and workforce data by region, figures for new and replacement workers needed, and recommendations on filling the gap in the welding education pipeline. The employment projection data is continuously updated and currently shows a need for over 310,000 welders, inspectors, technicians, and engineers by 2019.

The comprehensive reform of welding technician education. In 2011, the Weld-Ed Center published a national core curriculum model. This core curriculum, appropriate for all postsecondary Welding Technician education programs, provides a validated listing of the core of what students should know and be able to do after completing a welding technician program. A student learning outcome specifies what a student should learn as a result of their education experience in the classroom and laboratory. That experience might also include internships or other industry experiences. An outcome reflects the consequences or results of what the student learns, not what the instructor teaches. The student learning outcomes listed in the model are not intended to describe every conceivable student learning outcome that a postsecondary welding technician program might include. In fact, it is expected that most programs should include additional student learning outcomes that are germane to the specific location where students may be employed.

Enhance faculty professional development and continuing education. Weld-Ed has developed a series of professional development modules for secondary and post-secondary educators. These modules incorporate the list of student learning outcomes from the national core curriculum model and thus prepare educators for successful instruction in a welding technician program. The core professional development program includes four modules, typically offered in the summer months, with each module consisting of one week of instruction.

Welding metallurgy and weldability of commercial alloys. This course covers the concepts and fundamentals of atomic structure, grain structure, heat flow, phase transformations, welding metallurgy, and the weldability of ferrous and non-ferrous commercial alloys. Laboratory work consists of welding metallurgy investigation on welded samples and weldability testing for specific applications.

Cutting and joining processes. This course covers the basics and principles of major joining and cutting processes. Advantages, disadvantages, equipment, consumables, techniques and variables for each process are discussed. Applications, criteria for consumable selection, and how to establish process parameters are emphasized. Laboratory work involves equipment set up and operating of the welding and cutting equipment for specific applications.

Design for welding, fabrication, assembly and robotic welding. This Course Covers The concepts and fundamentals of the design for welding, fabrication, assembly and robotic welding. Laboratory work consists of case studies using standard design equations to determine the behavior of welded materials, part processing and optimization of fabrication, design considerations for work holding and manipulating equipment, and the programming and operating of robots for GMAW welding.

Weld quality and inspection, welding codes, specifications and safety. This course covers the concepts and fundamentals of weld quality and inspection methods, welding codes, specifications, and safety. Laboratory work consists of setting up and operating the instruments and equipment for identification and characterization of weld discontinuities and defects.

These four professional development modules have been offered for three summers to over 275 educators. The success of these core modules led the Weld-Ed team to develop two additional one-week modules to be offered for the first time in summer 2013. These include the following:

Laser welding. This course covers the concepts and fundamentals of laser welding technology including basic optics, laser welding systems and welding process optimization, and metallurgy of laser welds. Laboratory work consists of case studies that involve optimization of laser welding equipment and identification and characterization of weld discontinuities and defects.

Efficient and effective welding technician instruction. This course covers the foundations of welding technician education; program needs assessment and program development, developing program and course objectives, a survey of learning theory, laboratory development, teaching methods, and classroom management techniques.

In addition, Weld-Ed offers an annual Educators Conference in conjunction with the FABTECH show. This one-day conference is open to educators and industry trainers and features updates on Weld-Ed offerings, best practices from educators, and presentations and free resources from Weld-Ed industry partners. More than 200 individuals have taken advantage of this outstanding programming over the past few years.

As Weld-Ed looks to the future, plans include continuous improvement of the existing professional development modules; expansion of professional development opportunities to include the advanced needs of industry; investigation into new delivery approaches for education and training such as on-line and blended delivery; growth of offerings to include consulting in needs assessment, program design, program improvement; identification of future strategies to sustain the existence of the Center.

AWO — American Welding On-Line. AWS statistics of the welding industry in the United States show an abundance of school programs dedicated to the entry-level and advanced-level welding, but precious few programs dedicated to welding supervision, inspection, or engineering. As the welding certification body in the United States, AWS provides some training in the bodies of knowledge for each of these fields, but that training has historically been limited to survey courses helping students review prior to examination. These courses are not designed to instruct on fundamentals, nor are they meant to teach the subject to individuals interested in entering those career fields. Rather, these courses are developed for individuals already functioning in those roles to fill in knowledge gaps in preparation for examination. Individuals seeking to enter into one of welding careers fields with little or no prior knowledge are most commonly left to rely on self-study. Recognizing this shortcoming, the American Welding Society is utilizing American Welding Online as a means of establishing profession pathways for individuals seeking to advance their careers. Instead of teaching only the advanced knowledge needed for test preparation, American Welding Online courses span the gamut of knowledge levels from those who are looking to break into the field, to those who are well established. With the development of AWO, individuals will no longer need to seek out specialized schools or training programs to learn the variety of skills needed to obtain an AWS Certification. Clear, interconnected curriculums provide the learner with career pathways that can take them from entry level to certification.

AWS recognizes that in order to close the widening skill gap in the welding industry new means of training welding personnel are required. In an effort to address these issues, the American Welding Society developed American Welding Online (awo.aws.org). American Welding Online, or AWO, is a virtual educational community dedicated to training the welders and welding personnel of the future. The foundation of AWO is a simple principle: To provide welding education to anyone, anywhere, and at any time. In order to fulfill this mission, AWS has adopted a modular approach to American Welding Online.

The cornerstone of American Welding Online is the library of e-learning courses and virtual conferences offered by AWS. These seminars are offered asynchronously, allowing students from around the world to access the course content on their own schedule and complete the program at their own pace. The American Welding Society offers multiple levels of training and testing, from entry level certificate training to advanced certifications. Through American Welding Online, AWS currently offers several online courses including the Certified Welding Sales Representative Program, Welding Fundamentals, Safety in Welding, Math for Welders Level I, Understanding Welding Symbols, Welding Metallurgy, and the soon to be released The Science of Non-Destructive Testing, Welding Economics, and Lean Management for Welding Shops courses.

All American Welding Online courses are built to teach the necessary knowledge base while focusing on STEM (Science, Technology, Engineering, and Math) education. Unlike most welding education currently in the marketplace, AWO courses do not focus on the physical act of welding, but rather the theoretical base; the scientific and engineering principles; critical thinking; and problem solving. Courses, such the AWS Welding Fundamentals seminar, provide science-based education on six of the most common welding processes: Oxyfuel Welding, Shielded Metal Arc Welding, Gas Tungsten Arc Welding, Gas Metal Arc Welding, Flux Cored Arc Welding, and Submerged Arc Welding. The seminar provides in-depth study of these welding processes through the use of diagrams, animations, high-definition videos, and synchronized audio narration. The seminar study material is presented in a thoughtful way that challenges participants to think critically about the topics. For example, when reviewing Shielded Metal Arc Welding, the course does not simply review the basics of how the process works, instead it examines the practical application of SMAW, the science of the welding arc, and how various welding variables, such as travel speed or amperage affect the final weld. The seminar also integrates education on higher knowledge skills such as welding electrical theory, welding metallurgy, and welding discontinuities. The participants receive constant feedback and reinforcement in form of interactive elements, practice problems, quizzes, and in some courses, workbook practice. The combination of interactive instruction and constant feedback provides participants the opportunity to use high-level thinking skills and critical thought to understand deeper connections in the instruction material.

Almost as important as offering professional pathways, American Welding Online allows learners to take ownership of the educational process, customizing the experience to their individual needs. The on-demand training offered through AWO allows the user to determine which courses in the professional pathways are suitable for their knowledge level. This customized curriculum provides learners with the most time- and cost-efficient means of gaining the knowledge necessary to advance in their careers.

As of February 2013, American Welding Online began offering synchronous learning opportunities in the form of monthly webinars. These live training opportunities offer the individual the opportunity to learn from experts in a variety of fields from anywhere in the world. In addition to the ability to access this training from any computer in the world with an internet connection, these webinars allow the learner to ask direct questions to a live instructor/expert, network with like-minded participants, and contribute their own experiences to the educational process. In order to reach the largest number of individuals possible, AWO will also host recordings of these webinars on American Welding Online so that those individuals who could not attend can still access the information.

Aside from the asynchronous and synchronous learning opportunities offered through American Welding Online, AWS continually offers informal learning opportunities such as the Professional Program Podcast. This complimentary podcast can be downloaded to any portable device through the AWO Podcast page on i Tunes (https://itunes.apple.com/us/podcast/american-welding-online/id505523313) or watched directly through the AWO website. AWO will also be launching a series of phone and tablet apps geared towards allowing individuals to learn in informal environments. The AWS app library will consist of apps designed to help prepare individuals for the Certified Welding Inspector exam (both D1.1 and API 1104 versions), as well as virtual welding apps with both educational and entertaining aspects meant to draw interest to the welding field while educating the user through the use of a game.

With the advent of American Welding Online, the American Welding Society is realizing its goal of bringing welding education to anyone, anywhere, and at any time. This multifaceted response to the growing gap of skills and knowledge needed to compete in a global economy will ensure that all levels of the welding industry, whether the entry-level student or the professional, are provided the opportunity to obtain the education required for the technologically advanced jobs of tomorrow and today.

Conclusions

The worldwide need for skilled and educated welding professionals is recognized by those working in the field, but people who could potentially fill that gap must be reached. Therefore a concerted effort is underway to improve the image of welding and to reach the general public, as well as targeted populations, such as youth and women. Media such as publications, brochures, videos, DVDs, and TV personalities are targeting the general population. Youth are also targeted through Iron Man Comic Books, the virtual welders, BSA merit badge and social media. Women in welding are highlighted as role models to interest females and their parents.

Once persons are interested they need to be properly trained and educated. A variety of means of delivering those skills and education are underway depending on the location in the world. Most countries have schools, colleges and universities that teach welding. AWS in co-operation with Weld-Ed has programs to reach youth and to provide a model welding technology curriculum and courses for faculty professional development and continuing education. AWS has launched American Welding On-Line to provide a welding education to anyone, anywhere, at any time and dedicated to training the welders and welding personnel of the future.

These projects as well as others are focused on successfully educating the population on the needs and opportunities, then providing the training and education necessary for welding professionals to properly build our infrastructures and provide the workforce for energy production and many other industries.

1. (2011) *The Manufacturing Institute and Deloitte Consulting LLP Skills Gap Study*, July–August.
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Received 09.09.2013