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DEAR COLLEAGUES-WELDERS, PROFESSORS, TEACHERS, STAFF MEMBERS AND STUDENTS OF THE WELDING FACULTY OF THE PRIAZOVSKY STATE TECHNICAL UNIVERSITY AND THE CHAIR OF WELDING PRODUCTION OF THE CHERNIGIV STATE UNIVERSITY OF TECHNOLOGY

The Higher School of Ukraine occupies the leading place in Europe (second to Russia) by the level and quantity of graduating welding engineers. 20 chairs of 17 higher educational institutions of Ukraine qualified hundreds of engineers and masters. Over the passed 55 years the Chair of Welding Equipment and Technology of the PSTU has qualified more than 4900 specialists, and the Chair of Welding Production of the ChSUT — more than 1500 specialists during 30 years. Many of them became managers of the largest construction sites, enterprises, higher educational institutions of Ukraine and CIS. More than 110 graduates of the Chair and Faculty of the PSTU became Candidates of Sciences (Eng.) and 10 of them — Dr. of Sciences (Eng.).

We are pleased to note that the scientific potential of the higher school during the 1990s was not lost, but, on the contrary, it is constantly strengthening. In 2000 the research-pedagogical activity at the welding chairs was realized by 44 Professors, 39 Dr. of Sci. (Eng.) and 166 Cand. of Sci. (Eng.). 61 students finished the post-graduate courses.

The E.O. Paton Electric Welding Institute paid always a great attention to the research works of the higher educational institutions and at present maintains close relations with subject chairs of the universities of Ukraine. Over the recent years the Institute provides the chairs with analytical information and reviews about the progress in the world welding science and technology. Professors and teachers of the universities are always welcome participants of national and international conferences carried out at the E.O. Paton Electric Welding Institute. They are also active authors of the journal «Avtomaticheskaya Svarka». Thus, this issue of the Journal includes selected articles of teachers and specialists of the PSTU and ChSUT, which were prepared from the results of research works carried out during recent years.

The E.O. Paton Electric Welding Institute of NAS of Ukraine and the Editorial Board of the journal «The Paton Welding Journal» congratulate teachers, staff members and students of the Priazovsky and Chernigiv Universities, wish them every happiness, prosperity and new success in the education and training of specialists in welding and allied technologies.

Boris E. PATON

55 YEARS OF THE CHAIR OF WELDING EQUIPMENT AND TECHNOLOGY OF THE PRIAZOVSKY STATE TECHNICAL UNIVERSITY

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In 1946 the Chair of Welding Equipment and Technology was established at the Zhdanov Metallurgical Institute by the decision of the authorized bodies of the country. It was aimed at the education and training of specialists on welding and cutting of metals and also engineering personnel for newly organized production of electrically-welded pipes of the main pipelines. At the same time the preparation for putting the pipe welding shop No.1 at the Ilijch Works into service was finishing. This shop was created by the initiative and direct participation of academician E.O. Paton.

The first executive Head of the Chair in 1946 was A.Ya. Shadrin, and at the same year he was replaced by Dr. P.S. Elistratov. From the very first days the works were started on the creation of education-laboratory base of the Chair, organizing and development of research works in the field of welding of structures, restoration of metallurgical equipment components by surfacing. The first defence of diploma projects in the new specialty was in 1947. The first five graduates (D.P. Antonets, A.A. Filchakov, K.I. Korotkov, Yu.N. Grishchenko, D.A. Rogovin) became profound specialists and managers in welding fabrication, two of them (D.P. Antonets and D.A. Rogovin) defended theses for the Candidate of Engineering Sciences.

In August 1952 K.V. Bagryansky was elected the Chair Head. He started the reconstruction of the educational process, improvement of the laboratory base, widening and strengthening of relations between the Chair and the E.O. Paton Electric Welding Institute, I.E. Bauman Moscow Technical College, Kiev Polytechnical Institute and many enterprises of the city and country. A building of the Welding Chair was constructed with the assistance of academician B.E. Paton. This made it possible as far back as 1960s to improve significantly the education of specialists and to become this Chair leading among the similar chairs. Talented teachers and scientists were working together with K.V. Bagryansky, among them Z.A. Dobrotina, D.S. Kassov, G.S. Kuzmin, P.F. Lavrik, A.A. Filchakov, V.A. Muratov, V.T. Sopin.

Having based on unique educational-methodological developments of the Chair specialists the education of welding engineers of the new specialty «Metallurgy and processes of welding fabrication» was started since 1968. In 1971 the Faculty was organized, which included, except the welding chair, the general technical and educational chairs. The first dean of the Welding Faculty was Dr. D.P. Antonetz, who worked for many years as a Chief Welding Manager at the «Azovmash» Works.

In the 1960s the research activity of the Chair had a powerful spur under the supervision of K.A. Bagryansky. This activity was directed to the development of welding and surfacing using ceramic (agglomerated) fluxes and examination of properties of welded and surfaced products. Those years the process of nickel welding using the ceramic flux found a successful application at the «Bolshevik» Works in Kiev (G.S. Kuzmin — supervisor). Under the supervision of D.S. Kassov a method of welding and surfacing of copper alloys using the ceramic flux was developed and successfully implemented at the metallurgical works in Ukraine. K.V. Bagryansky with an active participation of V.Ya. Zusin and A.D. Korneev have developed a method of submerged arc welding of aluminium, which was widely used for welding elements of the current-carrying busbars at the Bratsk Hydroelectric Station. The process of surfacing with a ceramic flux found a wide application in restoration of rolling mill rolls and components at the metallurgical works in Rustavi (Georgia), Ilijch and «Azovstal» in Mariupol, Enakievo Metallurgical Works, Ore-dressing Works in Ust-Kamenogorsk (Kazakhstan). A.A. Filchakov supervised the research works on the development and implementation of new grades of electrodes at the «Azovmash», while K.A. Olejnichenko supervised the development of the procedure of a quantitative determination of harmful evolutions during welding. They issued recommendations for improving the welders' labour conditions.

During 1955 – 1980 30 theses for Cand. of Eng. Sci. and 1 thesis for Dr. of Eng. Sci. were prepared and defended. Textbook «Theory of welding processes» (K.V. Bagryansky, Z.A. Dobrotina, K.K. Khrenov) was republished three times and manual «Calculation and designing of welded structures» (A.N. Serenko, M.N. Krumbolt, K.V. Bagryansky), manuscripts «Welding of nickel and its alloys»

Royanov Vyacheslav A. — graduate of Zhdanov Metallurgical Institute (1963), Head of the Chair of Welding Equipment and Technology, Pro-rector, Professor, Academician of AN VSh of Ukraine.

Students of Welding Faculty of PSTU study design and mode of operation of robot «Brig-10»

(K.V. Bagryansky, G.S. Kuzmin) and «Ceramic fluxes for welding and surfacing» (K.V. Bagryansky) were published.

In 1971 a branch research laboratory (BRL) of surfacing was established, whose task was to study and develop new designs of mill rolls and rollers of machines of continuous casting of billets, surfacing technology, materials and automated equipment. The laboratory is headed now by Dr. V.N. Matvienko.

A large contribution was made by the Chair and BRL of surfacing to the study of susceptibility of welded joints to the hot cracking. The work was carried out under the supervision of K.V. Bagryansky, Ya.Ya. Grigoriev and V.E. Saenko. As a result, a new test procedure was offered and some author's certificates were obtained. A large attention was also paid to the examination of properties of the deposited metal operating at room and high temperatures (V.N. Kalianov, B.I. Nosovsky).

Since 1973 to 1979 the Chair was headed by A.N. Serenko. During this period the studies of static and dynamic strength of welded joints and structures were carried out, the works on investigation of a single-passed welding of 40 mm thick and more steels with a process programming were started. The results of investigations are summarized in several theses (Cand. of Eng. Sci.) and also found a practical application at the «Azovmash» and Shipbuilding Yard «Zaliv».

In 1980 the Chair was headed by L.K. Leshchinsky. In collaboration with the BRL of surfacing the new ceramic fluxes and flux-cored wires for electric arc surfacing of mill rolls and components of metallurgical equipment were developed. The investigations of processes of plate electrode submerged arc welding and surfacing were carried out. The results of investigations were implemented at the machine-building and metallurgical enterprises and summarized in theses (Cand. of Eng. Sci.) of Yu.V. Belousov, V.A. Shchetinina, V.N. Matvienko, V.P. Lavrik, A.V. Zarechensky. The works were active on the improvement of equipment for automation of surfacing processes and quality control of the deposited metal. Their results were reflected in thesis (Dr. of Eng. Sci.) of S.V. Gulakov. Research works in the field of plasma hardening, including that after surfacing found a wide development. Their results are given in manuscript «Plasma surface hardening» (L.K. Leshchinsky, S.S. Samotugin, I.I. Pirch, V.I. Komar).

Students of Welding Faculty during programming of welding robot operation

Since 1985 the Chair of Welding Equipment and Technology is headed by Prof. V.A. Royanov. With his participation, the material base is widened and strengthened, the educational process includes the disciplines of robotization of welding fabrication and new information technologies (at the course and diploma designing). The research works are carried out in the field of thermal spraying of corrosion- and wear-resistant coatings. The flux-cored wires for electric arc metallization were developed and implemented at the Kiev enterprise «Kievtraktordetal» and auto-repair enterprises of Poltava, Tashkent and other cities. Results of investigations are summarized in theses of E.V. Vojtsekhovsky (Cand. of Eng. Sci.) and V.A. Royanov (Dr. of Eng. Sci.).

During the period from 1989 till 2001 S.V. Gulakov, V.A. Royanov, L.K. Leshchinsky, A.D. Razmyshlyaev, S.S. Samotugin defended their theses (Dr. of Eng. Sci.) at the Chair. A.N. Serenko was awarded the title of Professor. There is a course for preparing Doctor's degree thesis and two persons are working at their theses. There is a Specialized Council at the Chair for the defending Candidate's theses on specialty 05.03.06 «Welding and Allied Technologies».

Over three recent years textbooks «Welding. Introduction to specialty» (A.N. Serenko, V.A. Royanov), «Defects in welded joints and coatings» (V.A. Royanov, V.Ya. Zusin, S.S. Samotugin), «Repair of machines using welding and related technologies» (V.A. Royanov, G.G. Psaras, V.K. Rubajlo) and manuscript «Magnetic control of weld formation during arc welding» (A.D. Razmyshlyaev) were prepared and published.

The Chair has an active collaboration with industrial and machine-building technical secondary schools of Mariupol city within the scope of a multistage education of specialists.

During 55 years the Chair staff qualified about 4900 engineers, including those for countries of Europe, Asia and Latin America, more than 40 Cand. of Eng. Sci., 8 Doctor's theses were prepared and defended, more than 25 textbooks and manuscripts, 600 scientific articles were published, more than 250 developments were protected by the author's certificates and foreign patents.

The Chair graduates A.D. Chepurnoj, T.G. Kravtsov, V.Ya. Zusin, V.I. Shchetinina, V.N. Kalianov defended successfully the Doctor's degree theses. Many graduates have become known specialists in the field of welding and heads of industrial enterprises of Ukraine, Russia and other CIS countries.

At present the Chair has 3 Professors, Dr. of Eng. Sci.; 1 Professor, Cand. of Eng. Sci.; 9 Assistant Professors, Cand. of Techn. Sci.; 1 Senior Teacher and 2 assistants. The Chair passed IV level accreditation by the Ministry of Education and Science in Ukraine. The Chair prepares specialists by the following specialties: «Equipment and technology of welding fabrication», «Automated electric welding processes and equipment», «Equipment and technology of improving wear resistance and restoration of machine parts».

Specialists of the Chair take an active part in the work of International Association «Welding». In parallel with a traditional cooperation with welding chairs of educational institutions of Moscow, St.-Petersburg, Chelyabinsk, Ekaterinburg, Tbilisi, Minsk, Mogilyov and other CIS cities the relations are established with foreign institutions and organizations, such as Institute of Welding (Gliwice, Poland), Miskolc University (Hungary), Harbin Institute of Technology (China), etc.

The Chair of Welding Equipment and Technology celebrates its 55th anniversary with a desire of further improvement of the educational-methodological process directed to the increase in quality of education of specialists.

EDUCATION OF SPECIALISTS AT THE WELDING FACULTY OF THE PRIAZOVSKY STATE TECHNICAL UNIVERSITY

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Priazovsky State Technical University, Mariupol, Ukraine

The Welding Faculty of the Priazovsky State Technical University (PSTU) has celebrated 30 years since its foundation. It was one of three welding faculties of the former Soviet Union. Today Ukraine alone has two welding faculties: at PSTU and at the National Technical University of Ukraine «Kyiv Polytechnical Institute» (NTUU). Assistant Professor D.P. Antonets, Candidate of Technical Sciences, was the first dean of the Faculty. Then at different periods the Faculty was headed by Prof. L.K. Leshchinsky (1975), Doctor of Technical Sciences; Prof. A.N. Serenko (1989), Candidate of Technical Sciences; and Assistant Professor Yu.V. Belousov (1990), Candidate of Technical Sciences. Since 1999 up to now the dean's office has been headed by Prof. A.D. Razmyshlyaev, Doctor of Technical Sciences.

The Faculty consists of five chairs, including for Welding Equipment and Technology (Head of the Chair — Prof. V.A. Royanov, Academician of the Academy of Sciences of Higher Education of Ukraine, Doctor of Technical Sciences), Welding Metallurgy and Technology (Head of the Chair — Prof. V.V. Chigarev, Academician of the Academy of Engineering Sciences, Doctor of Technical Sciences) and Materials Science (Head of the Chair — Prof. L.S. Malinov, Member of the New York Academy of Sciences, Doctor of Technical Sciences).

Prominent scientists — professors, doctors of technical sciences V.K. Bagryansky, A.I. Gedrovich, G.V. Kuzmin and V.N. Kalianov —- were working at the Faculty in different years. Now the staff of the Faculty includes academicians A.D. Chepurnoj, V.A. Royanov, V.Ya. Zusin, professors L.S. Malinov, A.N. Serenko, S.V. Gulakov, S.S. Samotugin, and others.

Organization of the educational process, pedagogical and research activity at the Faculty is run now by highly qualified teachers: 1 academician of the Academy of Sciences of Higher Education of Ukraine, 3 academicians of the Academy of Engineering Sciences, 4 members of foreign academies of sciences, 10 doctors of technical and physical-mathematical sciences, 11 professors, 32 assistant professors, candidates of technical sciences and more than 30 senior teachers, teachers and assistants.

Chairs of the Faculty are fitted with modern research equipment. Substantial part of the R&D results has been applied in industry at a number of enterprises of Ukraine and other CIS countries. Main lines of the R&D activity of the Faculty include repair of technological equipment by different spraying methods,

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Shaferovsky Viktor A. — graduate of PSTU (1997), Assistant Professor of the Chair of Welding Equipment and Technology, Deputy Dean of the Welding Faculty.
Belousov Yury V. — graduate of Zhdanov Metallurgical Institute (1964), Assistant Professor, working for a Doctor's degree at the Chair of Welding Equipment and Technology.

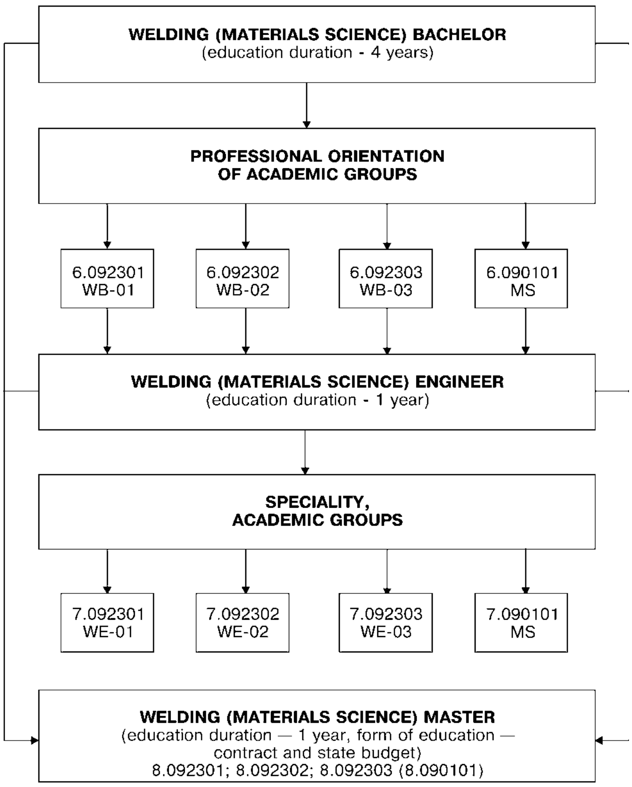
surfacing of rolling mill rolls, electric arc surfacing and welding using controlling magnetic fields, mechanized submerged-arc welding of heavy sections of metal with programmed process parameters, improvement of methods for increasing performance of welded joints and structures, evaluation of the stressed state of welded joints and parts with protective coatings, wear-resistant surfacing of metallurgical equipment parts, development of sparsely-alloyed high-strength and wear-resistant steels, investigation of physical phenomena occurring on the surfaces of solids and heat and mass transfer processes occurring at macro- and microlevels, formation of high-power plasma flows and their interaction with condensed media, etc.

Based on the research results, associates of the Faculty published more than 1000 scientific papers, including 10 books and manuals, and received over 100 author's certificates and patents.

The Faculty has a computer class, arranged in 1995. The class has 16 seats and is equipped with modern computer facilities.

The first graduation of welding engineers at the Zhdanov (Mariupol) Metallurgical Institute was in 1947. The number of graduates increases every year, and now it amounts to 4900 people. Before 1996 the annual number of school leavers admitted to the Welding Faculty was about 100 people.

In 1994 the Mariupol Metallurgical Institute was transformed into the Priazovsky State Technical University and certified for the IV level of qualification. From 1993 till 1997 the Welding Faculty of PSTU educated welding bachelors (WB) in four areas of professional orientation, corresponding to the following specialities: 8.092301 «Welding Production Equipment and Technology», 8.092302 «Technological and Metallurgical Welding Processes», 8.092303 «Automated Electric Welding Processes and Machines», 8.092304 «Equipment and Technology for Increasing Wear Resistance and Repair of Machine Parts», as well as specialists (in technical specialities called engineers — WE) and Masters (WM) [1].



Structure of education of specialists at the Welding Faculty of PSTU

At the end of 1998 the Chair of Materials Science joined the Faculty. In that same year the Ministry of Education and Science of Ukraine decided to change names of some specialities, such as 0923 «Welding» and 0901 «Applied Materials Science».

Therefore, since 1998 the Welding Faculty of PSTU has been educating WB, specialists (engineers) and WM in the following specialities:

- 8.092301 «Welding Technology and Equipment»;
- 8.092302 «Welding Machines»;
- 8.092303 «Technology and Equipment for Repair and Increase in Wear Resistance of Machines and Structures»;
- 8.090101 «Applied Materials Science».

The program of the 4-th and 5-th degrees [2] has been used as the basis of the concept of a multi-level system of higher education, which is common (baseline) now for all higher education institutions of Ukraine.

The stage of education for the WB degree in the above specialities is completed by preparing the diploma (qualification) work and its subsequent defence to the State Qualification Commission (SQC), providing that exams of the VIII term have been successfully passed. The WB diploma work is a final work, summarizing four years of studies at the University, and is intended for systematization, confirmation and widening of the theoretical knowledge by independently studying the subjects related to one of the branches of welding production or applied materials science.

Composition and scope of the diploma work are determined by a corresponding chair. As a rule, the diploma work consists of an explanatory note with a volume of not more than 60 pages of format A4, prepared in the form of a manuscript, and a graphical part for 4 – 5 sheets of format A1.

When assigned to practical work in industry, students receive individual work statements which specify units (pieces), the technology of the manufacture of which they should study. While preparing bachelor's diploma works, students develop new or improve known (baseline) technological processes used for the manufacture of these units. While preparing diplomas for the specialist's degree, students use, as a rule, basic developments made while preparing their bachelor's diplomas.

WB, having the baseline higher education, may receive the full higher education and qualification of a specialist (engineer) in four specialities by passing the second stage of education (see the Figure). Engineering education of WB lasts two terms and is completed with defence of a diploma to the State Examination Commission (SEC).

Realization of the WM education program in welding specialities started in 1995, following the special plans of studies based on the engineering education [1]. In compliance with the Resolution of the Cabinet of Ministers of Ukraine No.65 of January 20, 1998 (Provision of Education-Qualification Levels), since 1999 the Faculty has been educating masters, based on the qualification of bachelors and specialists.

In general, education of WM at the Faculty is carried out following the schematic shown in the Figure.

It should be noted that after receiving the qualification of a bachelor, further studies take one year (two terms) and are paid from the state budget, whereas after receiving the qualification of a specialist (engineer) the studies of a student working for a master's degree also take one year (two terms) but are provided mostly on a contract base.

In both cases candidates for receiving the master's degree should have positive references of the corresponding chairs and scientific boards of the Faculty and University. In addition, the University established a quota on a number of those admitted for receiving the master's degree, which is equal to 20 % of the total number of graduates having a higher education.

Studies for a master's degree are completed with preparation and defence of the diploma to SEC.

In our opinion, the quality of education of the staff under conditions of a multi-level system of higher education directly depends upon solving a number of problems [1]: raising the level of education of school leavers; admittance to PSTU the graduates of technical schools and reverse rotation of students to the PSTU technical schools; ensuring compliance of the process of education of specialists with European and international standards; raising the scientific-and-pedagogical level of teachers and professors; improvement of the educational process by using the advanced technical education means, including computer facilities; improvement of the language and economical education of the graduates, etc.

The practice of admittance of graduates of technical schools as the second- and third-year students, which has been applied during the last eight years, has proved beneficial. As a rule, this category of students is characterized by a very serious attitude to studies and a high level of practical training. Plans of studies for the first and second terms for all specialities of the Faculty and plans of studies for the PSTU technical schools were finalized in 2000 with a purpose to reduce the number of those retaking examinations in some disciplines and facilitate the first stage of studies at the University. The first-year students, who are non-capable for any reason of continuing their education at the University, are given the opportunity to finish their education at one of the PSTU technical schools. This was made possible by including into the University in 1998 three technical schools: mechanical-metallurgical, machine-building and industrial, as well as a technical lyceum.

Further development of higher education in Ukraine is impossible without allowance for the world and European experience in training of specialists, as well as requirements of the international standards regarding education and certification of welding specialists [1].

The main requirement and the most important condition of development of the market economy is an improvement of the quality of products of all industries. Products of the welding industry most often fall in the category of critical structures. For this reason the factor of compliance of these products with the European and world standards is very topical.

The level of education of teachers and professors of the Welding Faculty is rather high. At present the number of those studying at the post-graduate courses and working for a doctor's degree is 13 and 3 people, respectively. During the last five-year period more than 30 teachers and staff scientists have improved their qualification through the system of courses permanently functioning at the University in the following areas: pedagogical skill, psychology and pedagogics, computer training, etc.

The Faculty provides an active language training to specialists. Optional studies of foreign languages, a language of business communication, are arranged annually.

Since 1998 PSTU has incorporated the Special Council on defence of theses for a candidate's degree in speciality 05.03.06 «Welding and Related Technologies». Every year students of the Welding Faculty take the first places in olympiads. In October 2000 there was the «Welding-2000» exhibition in Kyiv, where the Welding Faculty exhibited equipment and materials developed by its chairs in the last years. As proved by the results of the exhibition, the Welding Faculty chairs rank high in significance and efficiency of their technical developments.

The Faculty maintains permanent business and creative contacts with its graduates working in different industrial organizations, commercial structures, enterprises and educational institutions, which makes it possible to reveal the demand for specialists in specific qualifications.

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30 YEARS OF THE BRANCH RESEARCH LABORATORY OF SURFACING

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As was already noted, the research activity of the Chair of Welding Equipment and Technology, headed by Prof. K.B. Bagryansky, had a significant progress in the 1960s. This activity was directed to the creation of new methods of welding and surfacing, development of equipment for these processes and also study of properties of welded and surfaced products. To realize these tasks, a Branch Research Laboratory of Surfacing was established in August, 1971 and is working successfully now. This Laboratory is specialized in the development and implementation of new welding technologies, equipment and materials, in the field of the ferrous metallurgy in particular.

The Laboratory was headed by the scientists of the Chair, Prof. K.V. Bagryansky and Prof. L.K. Leshchinsky. At present it is headed by Dr. V.N. Matvienko. Prof. V.A. Royanov, the Head of Chair, renders assistance to the laboratory in conductance of research works and the solution of organizing problems.

Over 30 years of existence of this Laboratory the scientists implemented more than 50 research works in industry, most of them were at the level of inventions.

The Laboratory staff participates in the education of the students on the specialties 8.092303 «Technology and equipment for restoration and improvement of wear resistance of machines and structures».

The Laboratory specialists solve successfully the different actual problems for the restoration and strengthening of the equipment components. The main trend in the Laboratory work is the solution of the problem of increasing serviceability, improving service characteristics of the working tools and parts of rolling, metallurgical and power engineering equipment, which is subjected to the intensive wear during service, namely development of rational designs of working layers with a new complex of properties of the working surface of mill rolls and rollers of the machines for the continuous casting of billets, technique and technology of surfacing, surfacing of sparsely-alloyed materials, technology of plasma surface hardening, mechanical and automated equipment, non-standard (main and auxiliary) equipment for the realization of the preset problems.

The activity of the Laboratory was oriented from its very beginning to the practical needs of the industry. The high economical efficiency was obtained as a result of implementation of the research works for the restoration and hardening of mill rolls of slabbing-1150 and NShS-1700 of hot rolling, banded support rollers of plate mill TLS-3000, pilger mill rolls, rollers of machines for continuous casting of billets and other equipment of Metallurgical Works (OJSC «Iljich MMK» and «Azovstal»). For this purpose, the Laboratory of surfacing has developed, created and put into service the surfacing bays into LPTs-4500, TLS-3000 and into a shop of slabbing mill-1150 of «Iljich MMK», which are furnished with all the complex of equipment required for realization of the technologies developed. At present the bay on restoration of mill roll of NShS-1700 is being created.

From the first years of its existence the Laboratory carries out research works on the development of new surfacing materials. A series of alloying ceramic fluxes of grades ZhSN (ZhSN-5, ZhSN-5R, ZhSN-7) was developed for surfacing wear-resistant layers of metal in manufacture and strengthening of large-sized steel components for the hot rolling equipment (support and working rolls of sheet rolling and reduction mills, etc.) and the flux-cored wires PP-8ZhN and PP-35ZhN were developed for surfacing of rolls of bar-rolling and pilger mills. These materials possess the self-adaptability to service conditions, i.e. they improve service characteristics under the severe working conditions. The successful fulfilment of many works became feasible due to mastering of industrial production of the mentioned surfacing materials at the Dnepropetrovsk Hardware Works. During development of the materials the Laboratory cooperated very closely with the Chair of Materials Science of our University. To provide a better supply of the surfacing shop bays with electrode material the production of alloyed surfacing cold-rolled strip of different chemical composition was mastered at the OJSC «Iljich MMK» on the basis of results of the research works of the Laboratory.

First in the Laboratory the technology of surfacing of rolls made from high-carbon steels was developed, which were considered early hard-to-surface. In particular, the temperature conditions of surfacing, conditions of formation of properties of the deposited layer, characteristics of used surfacing materials were determined. The Laboratory staff participated ac-

Matvienko Vladimir N. — graduate of Zhdanov Metallurgical Institute (1977), Assistant Professor of the Chair of Welding Equipment and Technology, Scientific Supervisor of Branch Research Laboratory of Surfacing.
Gulakov Sergej V. — graduate of Zhdanov Metallurgical Institute (1970), Head of the Chair of Automation of Technological Processes and Manufacturing, Dean of the Faculty of Information Technology.

tively in the development, upgrading and mastering of the surfacing equipment and technology of restoration and hardening of mill rolls and other metallurgical equipment, and also in the creation of surfacing bays at several metallurgical enterprises. The many-year experience of service of the mill rolls of the reduction mills of the metallurgical integrated works OJSC «Iljich MMK», «Zaporozhstal» and «Krivorozhstal», working and support rolls NShS of hot rolling at the metallurgical integrated works OJSC «Iljich MMK», Novo-Lipetsk and Cherepovets confirmed the high efficiency of the offered materials and technologies.

The designs of deposited layers with a wear resistance, changing in length, depth and surface of the roll barrel have been developed and mastered, thus making it possible not only to increase the efficiency of the rolling mills and serviceability of the rolls, but also to improve the quality of the rolled stock, to increase the yield of efficient metal, to reduce rejections for cuttings, to decrease the skidding and to level the peak loads to a main drive of the reduction mill. The working surface in this case possesses the unique complex of properties, i.e. equal wear of the surface independently of the load, wear according to the required regularities, producing of quasi-composite alloys in small and large volumes.

The technologies have been developed which allow manufacture of mill rolls with different working layers: consisting of successive staggered regions of materials with a different level of hardness, ductility, wear resistance or consisting of deposited beads, whose separate areas are oriented relative to each other in such a way that to provide a high resistance of the working surface to the action of cyclic heat changes due to delay in the propagation of fire cracks, and also unchangeable conditions of metal entrapping over the whole period of service. To surface the offered structure, the new methods of surfacing, materials and automated equipment have been developed.

To register and control the temperature conditions of the products being surfaced in the Laboratory, a small-sized contact electron thermal indicator was developed which can record the metal surface temperature in the range of 100 – 750 °C.

A system of an automated designing of technological processes of surfacing of the metallurgical equipment components has been created which increases the efficiency of designing of the deposited layer of a complicated configuration using a computer technology. One of the main activities of the Laboratory from the beginning of its foundation is the improvement of the technology of a wide-layer hardfacing for increasing its productivity and quality. Methods of a strip electrode were developed and realized, providing a reliable joining of the deposited metal at a minimum dilution of the parent metal by the redistribution of the action of the heat source over the fusion front, control of mass transfer of the molten metal and shaping of the weld pool. The effect is attained by a shaping of the strip electrode and also by changing the position and ratio of mass rates of feeding several strip electrodes. For example, the two-strip electrode surfacing increases the productivity of the process up to 30 – 32 kg/h at a high quality of the deposited layer and negligible (7 – 8 %) share of the parent metal in the deposited metal.

To realize the method of surfacing with a shaped strip electrode a batch of devices was designed and manufactured in the conditions of a pilot plant of NPO TsNIITMash (Moscow) for feeding and simultaneous shaping of the strip. These devices showed high reliability during service under the industrial conditions of Plant of Power Machine-building (Chekhov city, Russia), PO «Atommash» (Volgodonsk city, Russia), Donetsk, Novo-Lipetsk and Konstantinov Metallurgical Works, «Iljich MMK» and others.

The Laboratory has created special methodologies and equipment for study and examination of peculiarities of processes of surfacing and testing of main properties of the deposited metal, such as technological strength, resistance to the formation of hot and cold cracks, delayed fracture, strength within the operating range of temperatures, hardness at elevated temperatures, resistance to thermal fatigue, wear resistance at elevated temperatures, contact fatigue, etc. These methodologies are also used successfully by the staff members of chairs of PSTU and other research and educational institutions.

The results of investigations of properties of surfacing materials and technologies were checked many times in surfacing many types of mill rolls made from different types of the alloyed steels. They proved the technical and economical advantages of research works of the Laboratory of surfacing. Four Doctor's and nine Candidate's theses were prepared and defended using the results of research works of this Laboratory. Four manuscripts were prepared and published, new surfacing materials, technologies and equipment were developed. Novelty and priority of the scientific developments of the Laboratory were approved by more than 150 author's certificates of the USSR and patents of Russia, USA, Great Britain, France, Sweden, Germany and other countries.

A significant contribution to the development of the Laboratory itself and also its separate scientific trends was made by Yu.V. Belousov, V.P. Ermolov, N.G. Zavarika, V.P. Ivanov, A.V. Kovalchuk, V.P. Lavrik, L.S. Malinov, B.I. Nosovsky, A.I. Oldakovsky, I.I. Pirch, G.G. Psaras, N.F. Ryzhov, S.S. Samotugin, K.K. Stepnov, V.I. Shchetinina.

FEATURES OF ELECTRODE WIRE MELTING IN SURFACING BY PLASMA-MIG PROCESS

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ABSTRACT

The influence of a hollow non-consumable electrode arc in surfacing by the plasma-MIG process on the mode of melting of flux-cored wire axially fed through the plasmatron channel, is determined. Its positive effect on the uniformity of melting of the wire core and metal sheath is established. It is shown that surfacing by plasma-MIG process can be performed at a lower current of the consumable electrode without short-circuiting of the arc gap and with minimal penetration of the base metal.

Key words: *plasma surfacing, surfacing modes, electrode melting, metal transfer, flux-cored wire*

One of the main requirements to the processes of flux-cored wire welding and surfacing, is provision of a uniform melting rate of the core and the metal sheath, having a low electric conductivity. In surfacing by the plasma-MIG process, the electrode wire is additionally heated at the expense of the heat of the hollow non-consumable electrode (HNCE) arc [1], and at increased stick-out — also of Joule heat of the flowing current [2].

Studying the features of electrode wire melting, depending on the main parameters of the mode, is required to determine the optimal conditions of welding and surfacing. In welding the main requirement, as a rule, is achievement of the maximal depth of penetration, and in surfacing — minimal dilution of the deposited metal by the base metal.

The weld form factor in plasma welding is largely dependent on the plasma gas flow pressure, the value of which is proportional to the square of current [3, 4]. The mode of electrode metal melting and transfer is also dependent on current.

Surfacing (welding) by metal electrode wire being one of the elements of plasma-MIG process, the type of transfer influences the condition and integrity of the plasma-shaping nozzle and circular non-consumable electrode, as well as the process stability. From this viewpoint preferable are the fine-drop and jet transfer with minimal spatter, that is found at high enough current densities. In surfacing, however, the current density should be minimal, in order to achieve a minimal penetration of the base metal, this being usually accompanied by globular transfer and greater spatter.

The aim of this study was to determine the optimal parameters of the surfacing mode by two criteria — maximum admissible current density and minimal penetration of the base metal.

Experiments were conducted, using flux-cored wire in PNAM-2 type plasmatron with the following connection: consumable electrode — workpiece to VDU-601 source with a flat characteristic at reverse polarity; non-consumable electrode (it being the inner nozzle at the same time) to a power source with a drooping characteristic at reverse polarity. Plasmatron and feed mechanism were fixed on a rack. Samples were mounted on a support and moved at the speed of welding, provided by a separate drive. The process of the arc ignition and burning, electrode melting and electrode metal transfer, was recorded by high-speed filming (up to 4000 frames per second) by SKS-1M camera with simultaneous recording of current of the camera neon bulb, and of welding current and arc voltage by a mirror-galvanometer oscillograph N-116.

Investigation of the nature of electrode wire melting in a HNCE plasma arc presents certain difficulties, caused by that the glow of the plasma arc column prevents recording the drops, the brightness of which is lower, than that of the arc. Therefore, additional counter lighting of the arc by a filament lamp with a flat luminous body was used, and the shape of the consumable electrode tip and the molten metal drop was observed against the background of the lamp filament [5].

Frame-by-frame interpretation and viewing of the filmograms showed that the plasma-MIG process in argon at the selected parameters of the mode can be accompanied by globular transfer of the electrode metal, transfer of medium-sized metal drops without short-circuiting and fine-drop transfer with a certain frequency.

In order to study the influence of HNCE plasma arc on the frequency of transfer and size of the drops, two series of experiments were conducted on flux-cored wire surfacing in the same unit under the conditions of a HNCE arc (plasma-MIG process) and

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free-running arc in the absence of a HNCE arc. In both cases the same values of the average arc current, electrode feed rate, gas flow rate and surfacing speed were specified, that were selected by experiment planning [6, 7].

Identical other conditions of both experimental series allowed such factors as influence of the flux-cored wire composition and diameter, dynamic characteristics of the power source and welding circuit, as well as shielding gas composition, to be eliminated from the optimization parameters. The influence of three linear factors on the melting and transfer mode in the plasma-MIG process and with the free-running arc was evaluated from five tests of each series. The plasma gas was argon. Surfacing speed was set to be constant (20 m/h), shielding gas (argon) flow rate being 10 l/min. Welding arc current was varied in the range of 200 – 340 A, plasma gas flow rate being from 8 to 16 l/min and plasma arc current was varied in the range from 80 to 180 A.

Procedure described in [8] was used for quantitative processing of experimental results, except for individual measurements of the drops from the frames. Drop weight m_d and transfer diameter d_{av} were calculated by the number of drop transfers (transfer frequency n_d). It is found (Figure 1) that in plasma-MIG process, the frequency of drop transfer rises 3 – 4 times on average with the increase of the current of HNCE arc. The weight and diameter of the separating drops decrease, respectively.

The density of current in the anode spot, located on the liquid drop, remains the same, while the spot area grows with current increase. Therefore, more heat comes to the drop, and since the surface tension factor of steel (and of the majority of other metals) decreases with the increase of its temperature, the level of critical current at which jet transfer starts, also decreases. Surface tension lowering accounts for achievement of jet transfer at smaller arc current, as well as in the case of addition of oxygen to the shielding gas [9].

One of the factors, influencing the transfer mode, is pinch-effect, promoting drop refinement and higher transfer frequency with current increase. In this study it is assumed that the impact of electromagnetic forces on drop transfer in the plasma-MIG process is qualitatively and quantitatively similar to the nature of their impact in a free-running arc.

Besides the usual sources of heat coming to the consumable electrode, heat evolution from the column of HNCE arc is an additional source in the plasma-MIG process. The specific heat flow from the column of HNCE arc is given by Stefan–Bolltzmann law as

$$q_r = C\left(\frac{T}{100}\right)^4,$$

where C is the proportionality factor; T is the body surface temperature. It can be assumed that coefficient C and surface temperature do not change within the limits of the selected mode parameters.

Thus, the amount of heat Q contributed to the drop by radiation, is directly proportional to exposure time and area of exposed surface of the drop F_d and electrode tip l_r:

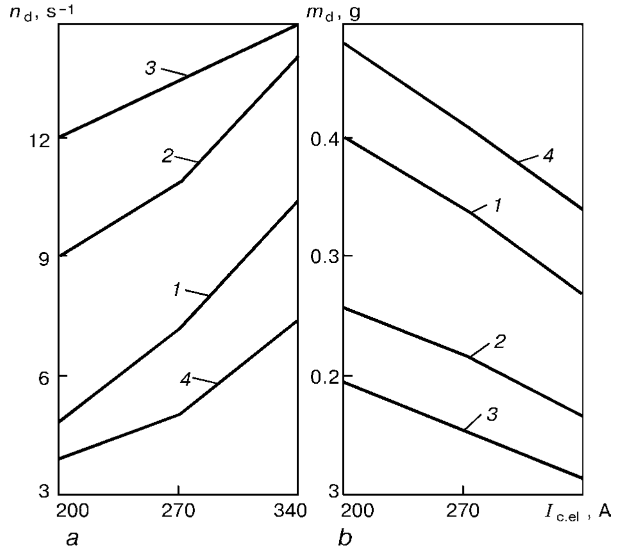

Figure 1. Influence of HNCE arc current I_{pl} on drop transfer frequency n_d (*a*) and weight m_d (*b*): *1* — I_{pl} = 80 A; *2* — I_{pl} = 130 A; *3* — I_{pl} = 180 A; *4* — free-running arc (I_{pl} = 0). Flow rate of plasma gas Q_{pl} (argon) — 8, shielding gas (argon) — 10 l/min

$$Q \equiv q_r t(F_d + \pi d l_r).$$

It is obvious that the main factor, influencing drop refinement in the studied process, is reduction of surface tension forces, as a result of additional heating through heat evolution from the HNCE arc column. Convective heat transfer can be neglected, as heat conductivity of argon is low (being 0.05 W/(cm·K) at 26000 K), and transfer is hindered by a comparatively cold gas flow. Additional heating of the electrode wire section, protruding from the non-consumable electrode, as well as of the drop, is due to radiation.

It should be noted that further heating by external radiation has a favourable effect on the nature of melting of the flux-cored wire tip (Figure 2). A very important advantage of the plasma-MIG process is uniform melting of the powder core and the metal sheath. The impact of the HNCE arc column promotes intensive melting of the core and axially symmetrical arrangement of the drops at the electrode tip. Despite the fact that the conical shape of the core is preserved, its length is reduced from 3 – 4 mm in the free-running arc to 2 mm in the plasma arc. Under such conditions, part of the molten metal of the sheath flows into the arc over the core surface. The frames of flux-cored wire melting show that under the conditions of the plasma-MIG process, the drop deviation from the electrode axis is practically not observed, that is attributable to smaller dimensions of the drops and positive impact of the plasma gas flow, «blowing off» the drops, deviating from the axis.

Aerodynamic impact of the plasma gas flow of the circular electrode is added to the impact of the plasma flow of electromagnetic origin, also directed from the electrode to the pool [10], thus promoting the increase of the number of drop transfers at lower current (see Figure 1). Despite these flows, however, shunting of the plasma arc is possible at globular transfer. Investigation of the plasma-MIG process at consumable electrode currents somewhat smaller, than the lower level ($I_{c.el}$ = 120 and 150 A) was carried out in addition to

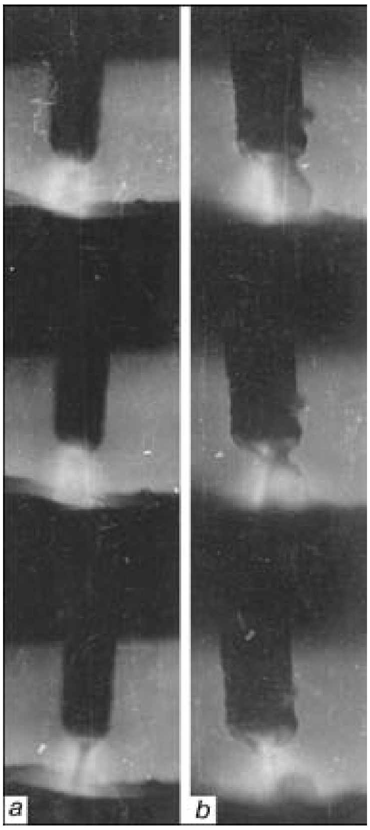

Figure 2. Filmograms of surfacing by plasma-MIG process at $I_{c.el}$ = = 270 (*a*) and 200 (*b*) A (I_{pl} = 130 A, argon flow rate — 10 l/min)

the experimental plan. At dimensions approximately equal to the inner diameter of the circular electrode, the drops deviate, and the column of the HNCE arc runs to the drop (Figure 3). Such a shunting can be also indicated by voltage decrease in both arcs.

The most optimal modes are those of medium-sized drop transfer, when the drop diameter is smaller, than that of the consumable electrode. For 2 mm flux-cored wire of the selected composition, this condition is satisfied at $I_{c.el}$ = 220 – 260 A, U_a = 30 – 32 V at the plasma arc mode parameters I_{pl} = 180 – 240 A, and U_{pl} = 40 – 42 V.

CONCLUSIONS

1. Additional thermal effect of the HNCE plasma arc in surfacing by the plasma-MIG process with flux-cored wire, promotes a more uniform melting of the core and the metal sheath, as well as axially symmetric formation of the drops at the electrode tip. It is found that with the increase of the HNCE arc current, and, therefore, of the temperature of heating of the electrode, as well as of the drop, by external radiation, the transfer frequency is essentially increased, while the drop size is reduced, accordingly, at unchanged current in the consumable electrode circuit.

2. A feature of the plasma-MIG process is the ability to perform surfacing at lower currents (compared to other arc processes of consumable electrode surfacing). Electrode metal spatter is almost completely eliminated and base metal penetration is minimized.

3. The most optimal transfer mode for surfacing by the plasma-MIG process is that eliminating shunting of the HNCE arc by the molten metal drops. Such conditions are implemented in the case, if the drop diameter is not greater, than that of the electrode wire.

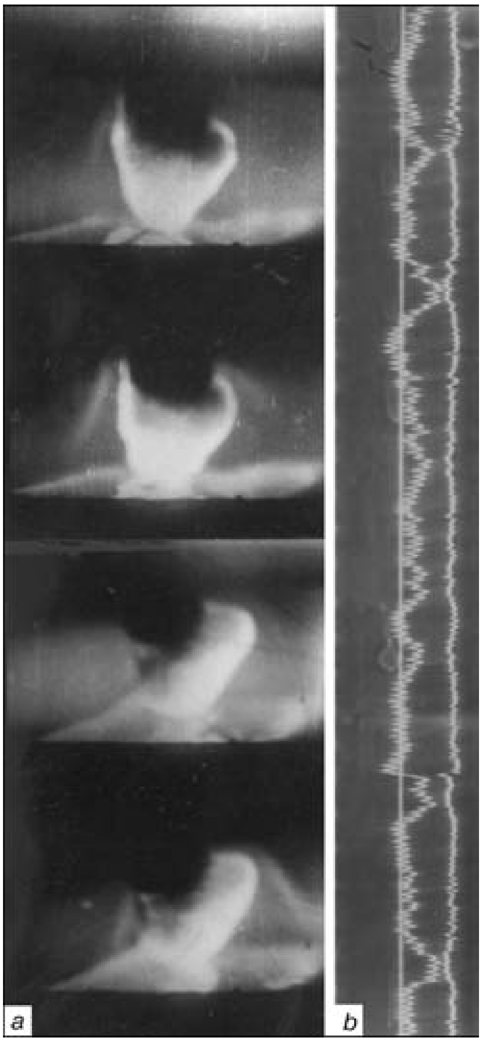

Figure 3. Filmogram (*a*) and oscillogram (*b*) of HNCE arc column closing by the electrode metal drop ($I_{c.el}$ = 120 A, I_{pl} = 130 A, argon flow rate — 10 l/min)

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DEPOSITION OF Br.AZh9-4 BRONZE BY ARGON-ARC SURFACING WITH THREE DISSIMILAR WIRES

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ABSTRACT

The possibility of producing a deposited layer of bronze Br.AZh9-4 in electric arc surfacing, using three dissimilar wires of copper, iron and aluminium is confirmed. Optimal wire feed rates and surfacing modes are established that provide the optimal required composition. The nature of variation of the deposited metal composition through the bead height is established, and the optimal height of the working layer deposit is recommended. Applications of the developed technology are described.

Key words: *bronze, surfacing, iron, copper, aluminium, torch, feed rate, distribution, coefficient, concentration, alloying, element*

Bimetal parts, produced by deposition of an aluminium bronze layer on a carbon steel base by arc surfacing, became widely accepted in order to save copper when making bronze inserts for rolling mill bearings, thrust bearings of jack carriages of converters, gears, pressure screw nuts, bushings, rims and many other items. Wires of Br.AMts9-2 and Br.AZhMts10-3-1.5 grades are used as surfacing materials.

Wire is not manufactured of aluminium-iron bronze Br.AZh9-4, because of a low deformability of this alloy, which is the most widely used in mechanical engineering for casting massive parts.

A technology of surfacing with three dissimilar wires by the schematic, given in Figure 1, was developed to produce deposited metal of a composition close to Br.AZh9-4 bronze. Alloying filler wires can be dead or can be at a potential of the same sign as the base metal. Applying such a technology and varying the grades of alloying filler wires, allows producing deposited metal also of other sought compositions.

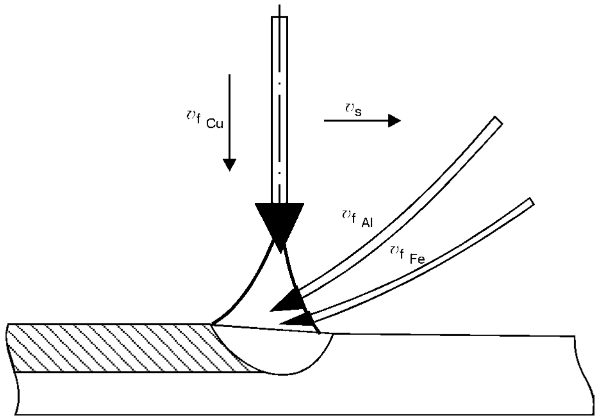

Figure 1. Schematic of Br.AZh9-4 bronze deposition by arc surfacing

Feeding additional filler wires into the arc zone, markedly lowers the penetration depth and reduces the amount of base metal in the deposited metal, this being essential in bronze deposition on steel (Figure 2).

Deposition is performed with the main 3.0 mm copper wire of grade M1, and 2.5 mm aluminium wire Sv-A5 and 2.5 mm carbon steel wire of Sv-08A grade are used as the alloying fillers.

Aluminium and iron content in the deposited metal depend on the diameter and feed rate of the aluminium and carbon steel wires, as well as diameter and feed rate of the main copper wire.

At the set feed rate of the copper electrode wire, the rate of feeding the aluminium wire to produce the specified amount of aluminium in the deposited metal, was established from the following dependence:

$$v_{f_{Al}} = \frac{C_{Al}\, D_{Cu}\, v_{f_{Cu}}\, K_{Al}}{C_{Cu}\, D_{Al}}, \qquad (1)$$

and the rate of carbon steel wire feed — from the following equation:

$$v_{f_{Fe}} = \frac{C_{Fe}\, D_{Cu}\, v_{f_{Cu}}\, K_{Fe}}{C_{Cu}\, D_{Fe}}, \qquad (2)$$

where $v_{f_{Al}}$, $v_{f_{Cu}}$, $v_{f_{Fe}}$ are the feed rates of aluminium, copper and carbon steel wires, respectively, m/h; C_{Al}, C_{Cu}, C_{Fe} are the proportions of aluminium, copper and iron in the deposited metal, %; D_{Al}, D_{Cu}, D_{Fe} are the diameters of aluminium, copper and carbon steel

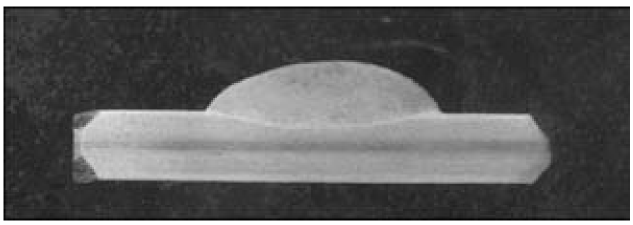

Figure 2. Macrosection of the deposited bead of Br.AZh9-4 bronze

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Figure 3. Microstructure of deposited bronze Br.AZh9-4 (×200)

wires, mm; K_{Al}, K_{Fe} are the coefficients, allowing for evaporation losses of the alloying aluminium and iron wires. The given coefficients were established experimentally: K_{Al} = 1.05 – 1.10; K_{Fe} = 1.02 – 1.05.

The following mode was optimal for DCRS argon-arc surfacing: I_a = 420 – 460 A, U_a = 32 – 36 V, v_s = = 14 – 18 m/h, $v_{f_{Cu}}$ = 80, $v_{f_{Al}}$ = 11 and $v_{f_{Fe}}$ = 6 m/h.

Argon flow rate was 25 – 30 l/min. As can be seen from Figure 2, in surfacing in the above mode, the penetration depth is insignificant, deposited metal is dense (no pores or cracks are observed). The high quality of the deposited metal is achieved at the expense of a reliable cleaning and degreasing (both mechanically, and by chemical etching) of the filler wires.

In terms of its composition, the multilayer deposited metal corresponds to bronze of Br.AZh9-4 grade and contains 8 – 10 % Al and 3 – 4 % Fe. Such a deposited metal has the following mechanical properties: σ_t = 500 – 550 MPa, *HB* 160 – 180. Figure 3 gives microstructural characteristics of deposited bronze Br.AZh9-4.

The developed technology of Br.AZh9-4 deposition by argon-arc surfacing with three dissimilar wires, that has passed production trials in surfacing of thrust bearings of converter jack carriages, provides a high quality of the deposited metal. It is versatile and its performance technique does not present any difficulties. The technology can be recommended for wide application in surfacing of critical items.

STRUCTURE AND PROPERTIES OF HAZ METAL OF LOW-ALLOYED PIPE STEELS MODIFIED WITH CALCIUM

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ABSTRACT

Diagrams of anisothermal decay of austenite for 13G1SU, 09G2FB, 10G2FB steels, modified with calcium, are plotted by the method of dilatometric measurements. The changes in structure of low-alloyed pipe steels under the action of the welding thermal cycle are shown. The constants of the exponential functions to describe for the polymorphous transformations are determined, the parameters of empiric equation, relating the impact strength values with a phase composition of HAZ metal are evaluated. It was established that the cooling rate within the 600 – 500 °C interval for 13G1SU, 09G2FB, 10G2FB steels should be within 5 – 35 °C/s, while at strict requirements to the structure — 8.5 – 35.0 °C/s.

Key words: *heat-affected zone, cooling rate, samples-simulators, microstructure, impact strength, thermokinetic diagram, linear energy input, heat input*

Today, the steels with a solid solution strengthening, including also those being calcium treated, are used for the manufacture of longitudinally-welded gas and oil pipeline pipes of a large diameter. The technology of producing these steels and a mechanism of the calcium action on their structure and properties are described in [1]. The positive characteristics (high strength and cold resistance) of the mentioned class of steels should be preserved also in welded joints.

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The main difficulty in welding is the prevention of an abrupt deterioration of properties as a result of appearance of structures, reducing the resistance to a brittle fracture in the HAZ metal.

There are only some information about the peculiarities of structure changes under the action of the thermal cycle for the main grades of pipe steels, which are deoxidized with calcium (13G1SU, 09G2FB, 10G2FB) [2, 3]. In this connection, the present work was aimed at the investigation of the regularities of the HAZ metal structure formation by simulating welding cycles on the samples of the pipe grades of steels, which were modified with calcium, at the determination of effect of the structure changes on the mechanical properties of metal and the selection of rational welding conditions using the methodology of structure examination, given in [4]. The chemical composition of the examined steel grades is given in Table. All they refer to the K55–K60 strength category and have the carbon equivalent of about 0.40.

The examination of the metal initial structure showed that all the as-delivered steels have a ferritic-pearlitic structure with a clearly-expressed line arrangement of ferrite and pearlite which is coincided with rolling directions.

Structural transformations were examined under the conditions of simulation of thermal cycles in a quick-response dilatometer of the design of the E.O. Paton Electric Welding Institute [5].

Maximum temperature of heating sample-simulators in the dilatometer was constant and amounted to 1350 °C, heating rate was 150 °C/s (within the 800 – 1000 °C temperature range). Range of examined cooling rates (within 600 – 500 °C) was 100 – 1.6 °C/s and corresponded to the cooling rates of welded joints made by CO_2 and submerged-arc welding [6].

The processing of the results of the dilatometric analysis and plotting of diagrams were carried out using the generally-accepted procedures.

The quantitative calculation of transformation products ratio was made from the dilatometric curves using the method of segments [7, 8].

The content of microstructure constituents was determined from GOST 8233–56. For this, the microsections were manufactured after the complete cooling of the samples-simulators. These microsections were also used for the hardness measurement. The sample microstructure was revealed by etching in 4 % solution of nitric acid, in ethyl alcohol, and examination and filming were made in microscope «Neophot-23» at 320 magnification.

Figure 1 shows thermokinetic diagrams of austenite transformation in steels 13G1SU, 09G2FB and 10G2FB under the conditions of the thermal cycle simulation. In the examined range of the cooling rates the austenite transformation is occurred in martensitic (M), bainitic (B) and ferritic (F) regions (10G2FB steel includes also the pearlitic (P) region). It is typical of all these steels that there is no pure martensitic transformation in them even at maximum cooling rate. The forming bainitic-martensitic structure has a comparatively low hardness (lower than *HV* 350). Only in 13G1SU steel it is higher (*HV* 358) due to, probably, higher content of carbon in it.

The calculation of quantity of phase constituents makes it possible to determine the impact strength of the HAZ metal and a desirable phase composition and, consequently a mean rate of cooling $w_{6/5}$ by processing the results of calculation using the preset limiting values of the impact strength. The known ratio [6, 9] for the calculation of quantity of phase constituents does not provide a sufficiently precise result for the steel grades examined.

The quantitative processing of the results was made using the exponential functions [10]. Thus, the content of martensite in structure (%) is amounted to

$$M = 100\left[1 - \exp\left(-k_m w^{n_m}\right)\right], \quad (1)$$

ferrite and pearlite content

$$FP = 100 \exp\left(-k_f w^{n_f}\right), \quad (2)$$

bainite content

$$B = 100 - M - FP, \quad (3)$$

where k_m, n_m, k_f, n_f are the constants; w is the cooling rate.

Equations (1), (2) are easily linearized that makes it possible to determine constants k_m, n_m and k_f, n_f from the experimental data of changing the content of martensite and ferritic-pearlitic mixture in sample metal at cooling rate variation:

Chemical composition of pipe grades of steels

Steel grades	*Elements, mass %*						
	C	*Mn*	*Si*	*S*	*P*	*Cr*	*Ni*
13G1SU	0.14	1.5	0.52	0.06	0.016	0.038	0.0045
09G2FB	0.09	1.62	0.26	0.04	0.017	0.03	0.03
10G2FB	0.11	1.65	0.24	0.05	0.017	0.03	0.03
Steel grades	*Elements, mass %*						
	Cu	*Al*	*Ti*	*V*	*Nb*	*As*	N_2
13G1SU	0.004	0.037	0.023	0.02	0.006	0.005	0.007
09G2FB	0.03	0.03	0.015	0.07	0.034	0.006	0.009
10G2FB	–	0.037	0.002	0.1	0.032	0.005	0.008

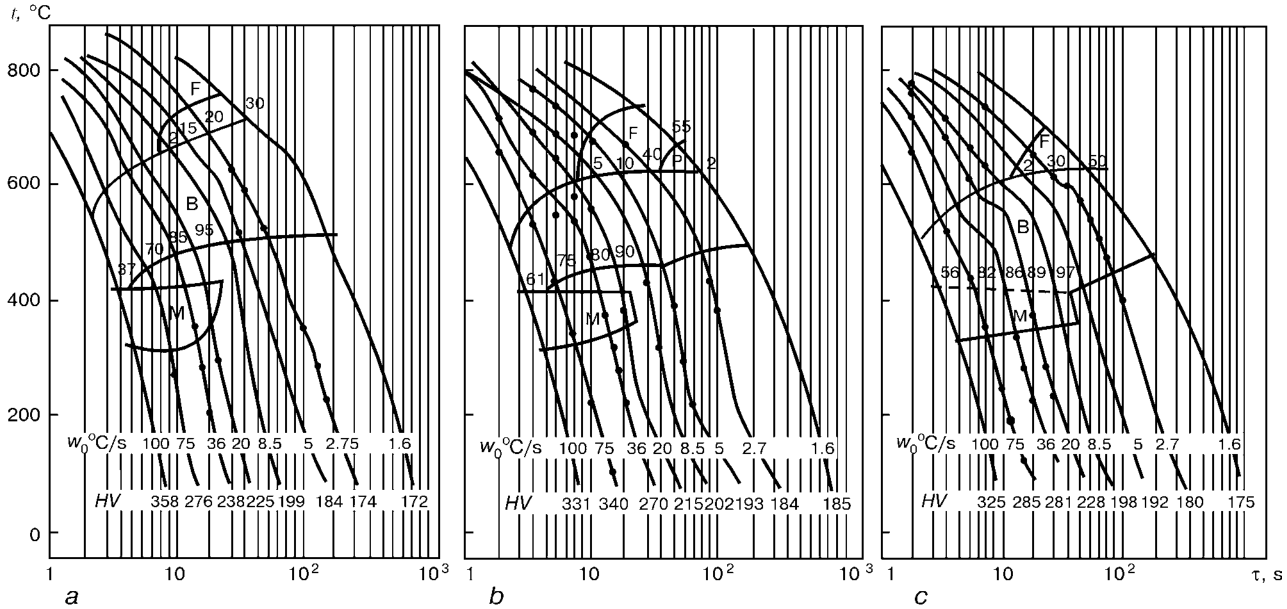

Figure 1. Thermokinetic diagram for steels 13G1SU (*a*), 09G2FB (*b*) and 10G2FB (*c*)

$$\ln[-\ln(1 - M/100)] = \ln k_m + n_m \ln(w), \quad (4)$$

$$\ln[-\ln(FP/100)] = \ln k_f + n_f \ln(w). \quad (5)$$

All the examined steel grades are characterized by close values of the carbon equivalent and their structural diagrams are described by the relations (1) – (3) with such coefficients: $k_m = 0.0021$, $n_m = 1.2$, $k_f = 0.487$, $n_f = 0.8$. The comparison of experimental data and results of calculations from equations (1) – (3), using the given coefficients, is shown in Figure 2. The experimental data have a good correlation with the results of the earlier investigations.

It is known that the HAZ metal structure has a good correlation with characteristics of mechanical properties. Thus, after processing the data [4] the following relationships between the characteristics of impact strength of the HAZ metal impact strength and its phase composition (J/cm^2) were obtained:

$$KCU_{-60} = -2.50M + 0.87B - 1.40FP, \quad (6)$$

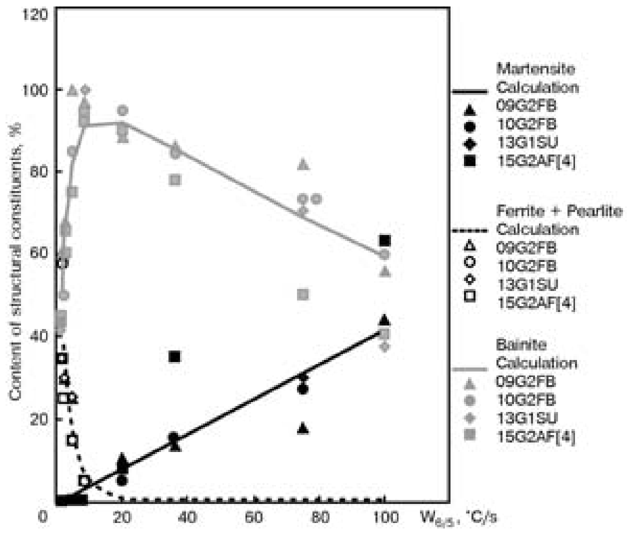

Figure 2. Structural diagrams for low-alloyed steels depending on the rates of cooling in a welding thermal cycle

$$KCV_{-40} = -0.864M + 0.505B - 0.661FP. \quad (7)$$

Relationships (6), (7) are adequate for steels with carbon equivalent of about 0.4 (results were checked using data of [9, 11]).

The similar relationship is known for the evaluation of KCU_{20} which is used for a wider range of varying the chemical composition of steels (MJ/cm^2) [12]:

$$\begin{aligned} KCU_{20} = {} & (1.06 - 2.8C^2 + 1.3C - 0.08Mn + \\ & + 0.054\ln(t_{8/5}))M/100 + \\ & + (1.3 - 1.6C - 0.08Mn)B/100 + \\ & + (1.47 - 1.8C + 0.8C^2 - 0.075Mn - \\ & - 0.045\ln(t_{8/5}))FP/100, \end{aligned} \quad (8)$$

where $t_{8/5}$ is the time of cooling from temperature 800 to 500 °C; C, Mn are the content of chemical elements in %. Relations (4) – (7) make it possible to set the limits which should include the cooling rate in welding thermal cycle (usually $w_{6/5}$) providing the phase composition of HAZ metal to obtain the satisfactory values of the impact strength. The solution of the system of equations (4) – (6) in relation to cooling rate $w_{6/5}$ showed that to keep the impact strength at the level of $KCU_{-60} \geq 40$ J/cm^2 the cooling should be made at rates in the ranges of 4.68 – 35.16 °C/s.

The analysis of microstructure of samples-simulators, cooled at rates 5.0 – 8.5 °C/s which provide the good characteristics of the impact strength showed that it is characterized mainly by a lower bainite. With a decrease in the cooling rate the quantity of an upper bainite is increased. The bainite becomes coarser with a formation of the structure which resembles the Widmannstatten structure and at $w_0 = 2.7$ °C/s the content of a structurally-free ferrite is increased in the structure. Therefore, the rates of cooling below 5 °C/s are not desirable (they do not provide the required values of the impact strength). The results obtained have a good correlation with data of [13].

Thus, the rational interval of cooling rates for the low-alloyed pipe steel grades is limited by the range of 5 – 35 °C/s (at more strict requirements to the HAZ metal — 8.5 – 35.0 °C/s). To solve the practical problems of pipe welding it is necessary to relate the cooling rate to the energy input.

In accordance with a diagram of the linear quickly-moving source the mean cooling rate (°C/s) within the range of 600 – 500 °C $w_{6/5}$ temperatures is determined using the formula [14]:

$$w_{6/5} = \frac{\pi\lambda c\rho}{(q/v)^2}\,[(600 - t_0)^3 + (500 - t_0)^3], \qquad (9)$$

where q/v is the energy input of welding; $q = \eta UI$ is the effective heat power of the heating source at a given efficiency factor η, arc voltage U and current I; λ, c, ρ are the heat conductivity, heat input and density of steel welded (from data of [14], for the low-alloyed steels λ = 40 W/(m·K), $c\rho$ = = 5.0 MJ/(m^3·K)); t_0 is the initial temperature of the workpiece being welded.

The energy input of welding, at which the desirable value $w_{6/5}$ is reached, amounts to

$$\frac{q}{v} = \delta\,[(600 - t_0)^3 + (500 - t_0)^3]^{1/2}\sqrt{\pi\frac{\lambda c\rho}{w_{6/5}}}. \qquad (10)$$

Calculation by equation (10) for the above-mentioned ranges of cooling rate makes it possible to find the limiting values of the welding energy input. At thickness of sheets being welded δ = 12 – 20 mm the lower limit of the energy input at $w_{6/5}$ = 35 °C/s should be within 8.9 – 14.8 kJ/cm, and the upper limit has the values 23.5 – 39.2 kJ/cm at $w_{6/5}$ = = 5 °C/s and 18.0 – 30.1 kJ/cm at $w_{6/5}$ = 8.5 °C/s. These values of the energy input are reached in practice (30 – 50 kJ/cm [15]) when the standard welding equipment is used.

CONCLUSIONS

1. Under the conditions of simulation of the thermal cycle at 100 – 1.6 °C/s cooling rates in low-alloyed pipe steels 13G1SU, 09G2FB, 10G2FB, modified with calcium, the austenite transformation is occurred in martensitic, bainitic and ferritic regions.

2. To preserve the impact strength of pipe steel welded joints at the initial level ($KCU_{-60} \geq 40$ J/cm^2) the cooling rate in HAZ metal should be within the 35 – 5 °C/s ranges.

3. For practical arc welding of pipe steels the mentioned cooling rates are reached in welding 12 – 20 mm thick sheets using conditions at which the energy input is in the range of 9 – 39 kJ/cm. These conditions can be realized in practice by the use of standard equipment and a specialized technique and technology of welding of the pipe manufacturing.

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CALCULATION OF MAGNETIC FIELD INDUCTION OF A SOLENOID WITH A FERROMAGNETIC CORE FOR ARC SURFACING

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ABSTRACT

The method of secondary sources was the basis to develop the procedure of calculation of magnetic field induction in the zone between the solenoid with a ferromagnetic core, generating a longitudinal magnetic field, and plate-workpiece. Optimal dimensions of the solenoid were calculated for the process of submerged-arc surfacing in a longitudinal magnetic field.

Key words: *arc surfacing, longitudinal magnetic field, ferromagnetic material, investigations*

New capabilities for controlling the geometrical dimensions of the penetration zone in submerged-arc surfacing with welding wire are opened up by the use of controlling longitudinal magnetic fields (LMF) [1 – 4].

A device for inducing the magnetic field (DIMF) in the form of a solenoid with cylindrical ferritic core coaxial with the electrode, is usually used for the processes of arc welding and surfacing in LMF [1 – 5]. In consumable electrode arc welding (surfacing) the ferromagnetic elements often are the welding wire, passing through the hole in the ferromagnetic core of the solenoid and the workpiece being welded (surfaced). At present there is no procedure for calculation of magnetic fields in solenoids, containing ferromagnetic components, this restraining the search for optimal dimensions of DIMF for the processes under consideration. Given below is a procedure based on the method of secondary sources [6], for calculation of the induction components of LMF generated by such axisymmetric DIMF (Figure 1).

Primary source of the magnetic field is constant current of density j, flowing through volume V_c of the coil that encompasses a steel core of volume V_{f1}, limited by surface S_{f1}. Secondary sources in this field are fictitious magnetic charges with bulk ρ_{m1} and surface σ_{m1} densities for the steel core and with surface density σ_{m2} for the ferromagnetic electrode. Relative magnetic permeability μ_1' of the steel core was assumed to be dependent on the co-ordinates and intensity of the magnetic field in a point, whereas magnetic permeability μ_2' inside ferromagnetic wire was taken to be constant. Intensity of equivalent magnetic field, expressed through the densities of all the sources, has the form of [6]

$$\mathbf{H}(Q) = \frac{1}{4\pi\mu_0} \int_{V_{f1}} \rho_{m1}(M1) \frac{\mathbf{r}_{M1Q}}{\mathbf{r}^3_{M1Q}} dV_{M1} + \frac{1}{4\pi\mu_0} \oint_{S_{f1}} \sigma_{m1}(M1) \frac{\mathbf{r}_{M1Q}}{r^3_{M1Q}} dS_{M1} + \frac{1}{4\pi} \int_{V_c} \frac{[j(N), \mathbf{r}_{NQ}]}{\mathbf{r}^3_{NQ}} dV_N + \frac{1}{4\pi\mu_0} \oint_{S_{f2}} \sigma_{m2}(M2) \frac{\mathbf{r}_{M2Q}}{\mathbf{r}^3_{M2Q}} dS_{M2}. \quad (1)$$

Densities of secondary sources were determined from the following relationships:

$$\rho_{m1}(Q) = -\frac{\mu_0}{\mu_Q} (\mathbf{H}(Q), \mathrm{grad}_Q\, \mu_1'), \quad (2)$$

$$\sigma_{m1}(Q) = 2\mu_0\lambda_{m1}(\mathbf{H}(Q), \mathbf{n}_{1Q}), \quad (3)$$

$$\sigma_{m2}(Q) = 2\mu_0\lambda_{m2}(\mathbf{H}(Q), \mathbf{n}_{2Q}), \quad (4)$$

$$\lambda_{m1} = \frac{\mu_1' - 1}{\mu_1' + 1}, \quad \lambda_{m2} = \frac{\mu_2' - 1}{\mu_2' + 1}, \quad (5)$$

where $\mathbf{n}_{1Q}$, $\mathbf{n}_{2Q}$ are the unit normals to the surface of the steel core and ferromagnetic electrode, respectively.

Substituting expression (1) into relationship (2) – (4) gives us a system of three integral equations

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$$
\begin{cases}
\rho_{m1}(Q) + \int\limits_{V_{f1}} \rho_{m1}(M1)\,\dfrac{\mathbf{r}_{M1Q}\nabla_Q\mu_1'}{4\pi\mu'(Q)\mathbf{r}^3_{M1Q}}\,dV_{M1} + \\
+ \oint\limits_{S_{f1}} \sigma_{m1}(M1)\,\dfrac{\mathbf{r}_{M1Q}\nabla_Q\mu_1'}{4\pi\mu'(Q)\mathbf{r}^3_{M1Q}}\,dS_{M1} + \\
+ \dfrac{1}{4\pi\mu_0} \int\limits_{S_{f2}} \sigma_{m2}(M2)\,\dfrac{\mathbf{r}_{M2Q}\nabla_Q\mu_1'}{4\pi\mu'(Q)\mathbf{r}^3_{M2Q}}\,dS_{M2} = \\
= -\mu_0 \int\limits_{V_c} \dfrac{[j(N),\,\mathbf{r}_{NQ}]\nabla_Q\mu_1'}{4\pi\mu'(Q)\mathbf{r}^3_{NQ}}\,dV_N, \\
\sigma_{m1}(Q) - \int\limits_{V_{f1}} \rho_{m1}(M1)\,\dfrac{\mathbf{r}_{M1Q}\mathbf{n}_{1Q}}{2\pi\mathbf{r}^3_{M1Q}}\,dV_{M1} - \\
- \oint\limits_{S_{f1}} \sigma_{m1}(M1)\lambda_{m1}(Q)\,\dfrac{\mathbf{r}_{M1Q}\mathbf{n}_{1Q}}{2\pi\mathbf{r}_{p_{M1Q}}}\,dS_{M1} - \\
- \oint\limits_{S_{f2}} \sigma_{m2}(M2)\lambda_{m1}(Q)\,\dfrac{\mathbf{r}_{M2Q}\mathbf{n}_{1Q}}{2\pi\mathbf{r}^3_{M2Q}}\,dS_{M2} = \\
= \dfrac{\mu_0\lambda_{m1}(Q)}{2\pi} \int\limits_{V_c} \dfrac{[j(N),\,\mathbf{r}_{NQ}]}{\mathbf{r}^3_{NQ}}\,dV_N, \\
\sigma_{m2}(Q) - \int\limits_{V_{f1}} \rho_{m1}(M1)\,\lambda_{m2}(Q)\,\dfrac{\mathbf{r}_{M1Q}\boldsymbol{n}_{\eta Q}}{4\pi\mu'(Q)\mathbf{r}^3_{M1Q}}\,dV_{M1} - \\
- \oint\limits_{S_{f1}} \sigma_{m1}(M1)\lambda_{m2}(Q)\,\dfrac{\mathbf{r}_{M1Q}\mathbf{n}_{2Q}}{2\pi\mathbf{r}'_{M1Q}}\,dS_{M1} - \\
- \oint\limits_{S_{f2}} \sigma_{m2}(M2)\lambda_{m2}(Q)\,\dfrac{\mathbf{r}_{M2Q}\mathbf{n}_{2Q}}{2\pi\mathbf{r}^3_{M2Q}}\,dS_{M2} = \\
= \dfrac{\mu_0\lambda_{m2}(Q)}{2\pi} \int\limits_{V_c} \dfrac{[j(N),\,\mathbf{r}_{NQ}]\,\mathbf{n}_{fQ}}{\mathbf{r}^3_{NQ}}\,dV_{N.}
\end{cases}
$$

This system of integral equations, allowing for the conditions of the magnetic charge sum being zero, was solved by block iteration method [6]. Non-linear properties of the steel core were incorporated from $\mu_1' = \mu_1'(|\mathbf{H}|)$ curve for the given steel grade. The plate being welded was modeled as a nonferromagnetic material, as well as a ferromagnetic material with constant ferromagnetic permeability. The plate ferromagnetic properties were allowed for by the mirror reflection method [7].

All calculations and experiments were conducted for solenoids with the number of coil turns $W = 20$ of 2.0 mm copper wire, when direct current $I = 42$ A is passed through it. Ferromagnetic core had a hole of diameter $d_{in} = 12$ mm. Coil height in all the experiments, except for the specially mentioned cases, was $H = 40$ mm, and the distance from the solenoid end face to the workpiece $h = 400$ mm. Welding wire Sv-80A (ferromagnetic material) of 5.0 mm diameter was used and the distance from the wire tip to the item was $\Delta = 5$ mm (Figure 1).

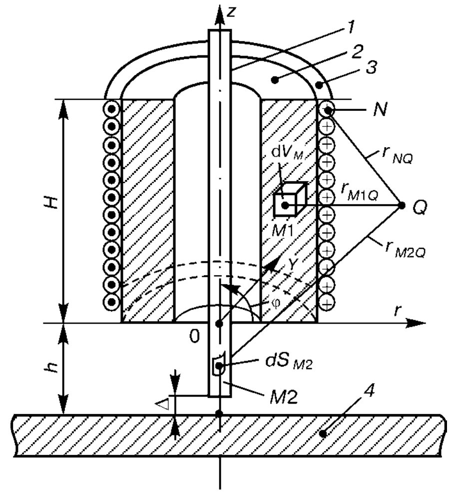

Figure 1. Schematic of a solenoid generating LMF: *1* — welding wire; *2* — core; *3* — coil turns (copper); *4* — workpiece

Search for the optimal outer diameter of the ferromagnetic core d_o was of interest, that would provide the maximal value of the longitudinal component of induction B_z of LMF at the surface of the ferromagnetic plate-workpiece (in the arc zone). Design and experimental data (in all the following graphs the lines correspond to the design data, and the signs — to experimental data) demonstrate that for a solenoid with the ferromagnetic core, induction value B_z grows practically linearly, if d_o is increased up to values of 60 mm, and with its further increase B_z values decrease (curves *3 – 5* in Figure 2). For a solenoid without the ferromagnetic core, induction component B_z grows with the increase of d_o up to 152 mm (curves *1, 2* in Figure 2). Here and further a good correlation between the experimental and design data should be noted. Thus, application of the ferromagnetic core allows not only a 2 – 3 times increase of induction B_z of the workpiece under the electrode (at $d_o \le 60$ mm), but also an approximately 3 times decrease of the solenoid diameter, making DIMF design more compact.

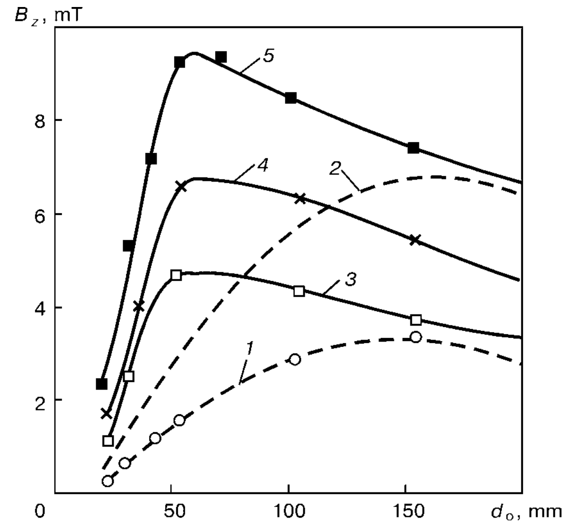

Figure 2. Dependence of induction B_z on solenoid core diameter d_o: *1, 2* — core of a nonmagnetic material (*2* — ferromagnetic workpiece); *3 – 5* — ferromagnetic core (*4* — ferromagnetic workpiece, *5* — ferromagnetic welding wire)

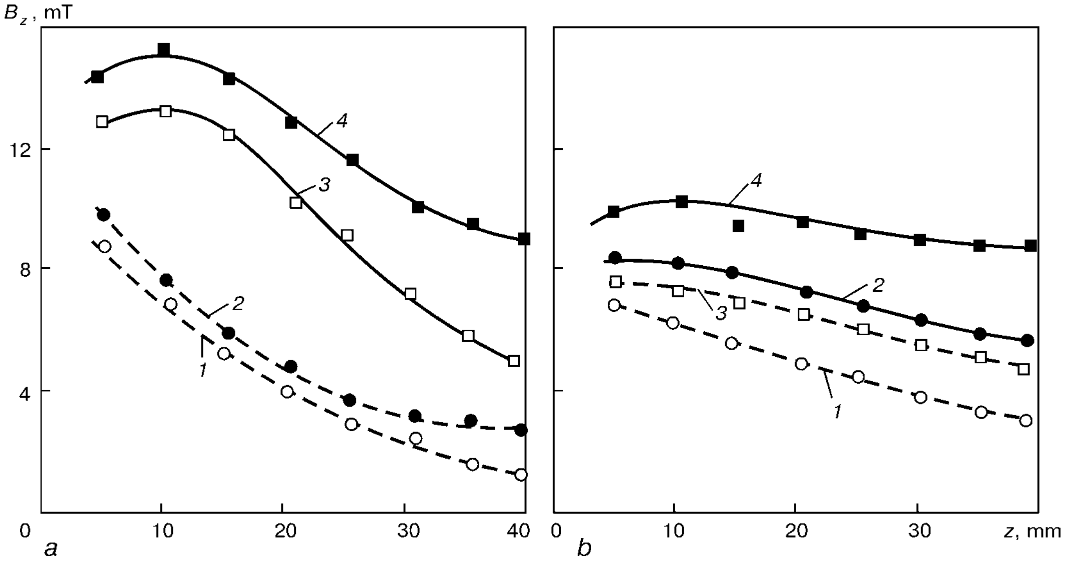

Figure 3. Distribution of induction B_z along axis 0z (r = 0) at d_o = 50 (*a*) and 100 (*b*) mm: *1*, *2* — core of nonmagnetic material; *3*, *4* — core and welding wire (*2*, *4* — ferromagnetic workpiece)

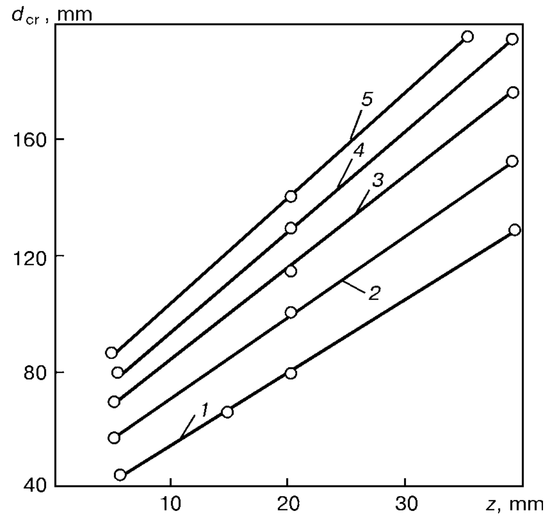

Figure 4. Dependence of solenoid critical diameter d_{cr} on distance $z = h$ (r = 0) at H = 20 (*1*), 40 (*2*), 60 (*3*), 80 (*4*), and 100 (*5*) mm

The rate of decreasing of induction component B_z in the direction from the solenoid core end face towards the workpiece is lower in the presence of a ferromagnetic core (curves *3*, *4* and *1*, *2* in Figure 3). With the increase of solenoid diameter, induction component B_z along axis 0z is distributed more uniformly (curves *1* – *4* in Figure 3, *a*, *b*). Similarly (data not given), the rate of decrease of induction values B_z along the radius in the direction away from the solenoid axis, is lowered, if solenoid diameter is increased. Thus, magnetic field becomes more uniform in this space, if solenoid (core) diameter is increased.

For solenoids without ferromagnetic parts (core and welding wire) and in the absence of a ferromagnetic workpiece, its crictical diameter d_{cr} can be determined, above which induction B_z does not increase, but decreases in a certain point on its axis. Calculations show that with increase of the distance along axis z at $r = 0$ ($z = h$ in Figure 1), d_{cr} values increase linearly. With the increase of height H of solenoid coil, d_{cr} values also increase (Figure 4). Similar dependencies are found for solenoids, containing ferromagnetic components, these dependencies being, however, rather weakly expressed. When the solenoid

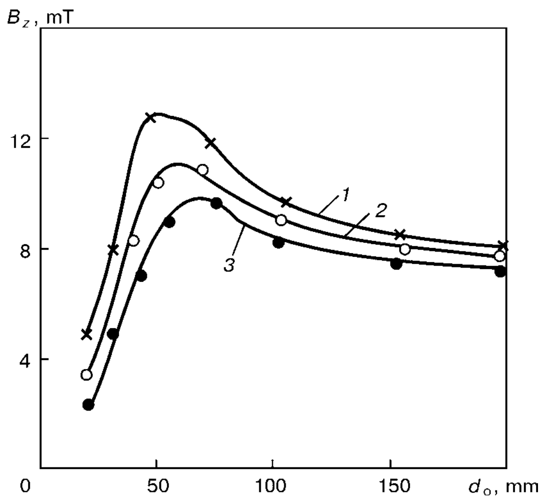

Figure 5. Dependence of induction B_z on diameter of solenoid ferromagnetic core d_o (workpiece and welding wire are ferromagnetic) at H = 20 (*1*), 30 (*2*), 40 (*3*) mm, respectively

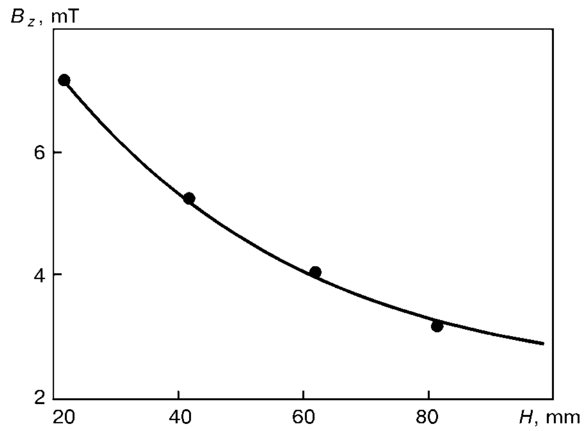

Figure 6. Dependence of induction B_z on height H of solenoid coil (d_o = 30 mm, welding wire and workpiece are ferromagnetic)

incorporates a ferromagnetic core and 5 mm wire, passing through a hole of diameter d_h = 12 mm in the core, as well as a ferromagnetic plate, shortening of distance $z = h$ from 40 to 20 mm results in the criticial diameter d_{cr} decreasing from 60 to 50 mm (Figure 5).

At the same magnetization force of the coil IW = = const, reduction of its height H allows increasing induction B_z of the workpiece under the electrode (Figure 6). Induction component B_z increases with the increase of the welding wire diameter. Thus, it is necessary to reduce coil height H of the solenoid to a reasonable extent, and perform deposition with the maximal (as far as possible) welding wire diameter.

CONCLUSIONS

1. The procedure, based on the secondary source method, for calculation of the magnetic fields generated by a solenoid with ferromagnetic parts, provides a satisfactory agreement of the design and experimental data.

2. Performed design-experimental work allowed recommending optimal solenoid dimensions for the case of submerged-arc surfacing with welding wire in LMF.

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INVESTIGATION OF THE PROCESS OF FLUX MELTING BY THE ARC

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ABSTRACT

Concepts of flux melting by thermal radiation of the arc column in electric arc welding have been analysed. It is established experimentally that the main thermal effect is produced by a plume formed in a running arc. Its physical impact is observed simultaneously, being manifested in formation of flows in the slag that transfer the heat from the plume to peripheral zones.

Key words: *arc welding, arc column and plume, flux melting, weld pool*

At present SAW is one of the most widely used (in full-scale production and repair) processes for structural element joining and coating deposition. In this case, the quality of welded joints is largely determined by the conditions and nature of the flux melting.

The flux melting theory existing for more than fifty years [1] is based on the assumption of the main energy contribution of arc column radiation into this process. A number of discrepancies between the theoretical prerequisites and practice were noted at the same time. In particular, no connection is found between the arc column temperature and relatively small weight of the slag, while it is known that heat removal through radiation is proportional to the fourth power of radiation temperature. Published data indicated that increase of welding current from 300 up to 800 A, raising the arc column temperature by 750 °C, leads not to an increase, but to a considerable decrease of the relative weight of the slag. Arc voltage rise, practically not influencing its temperature, causes an essential increase of flux melting effectiveness. The role of weld pool metal in this process was demonstrated later [2]. Discussion of the nature and physics of flux melting still goes on [3, 4], this being indicative of the urgency of this subject and its insufficient understanding so far.

It should be noted that flux melting is affected by several components, inherent to the arc welding process, namely the arc; heated and molten electrode and base metals; shunting current running through the molten slag. The proposed study was an attempt at determination of the role of the arc in flux melting

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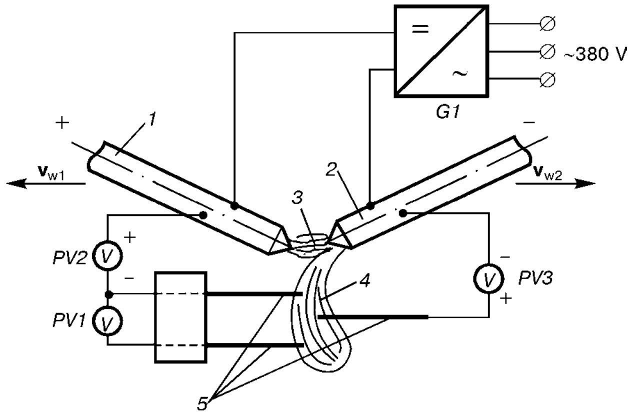

Figure 1. Schematic of probing a DC electric arc running between graphite electrodes (for designations see the text)

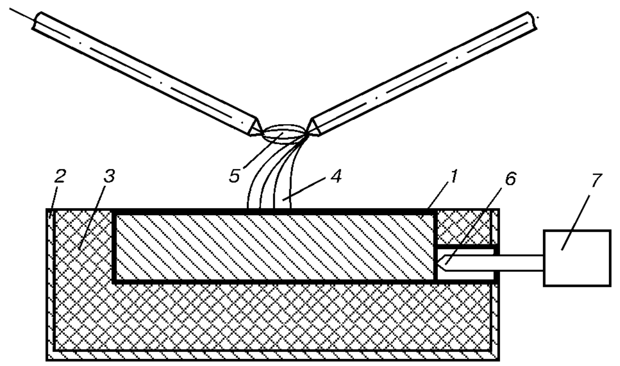

Figure 3. Schematic of measurement of energy characteristics of the arc plume (for designations see the text)

and evaluation of the contribution of its individual components. The first is possible, provided the weld pool is excluded from this process. In this connection, experiments were conducted on melting AN-60 (SiO_2 — 42.5 – 46.5; MnO — 37 – 41; CaO — 3 – 11; MgO — 0.5 – 3.0; CaF_2 — 5 – 8 wt.%) flux by a non-transfered arc running between nonconsumable graphite electrodes of 8 mm diameter. The arc was powered from VDU-1201 welding rectifier in the mode with a flat volt-ampere characteristic. The experimental set-up is shown in Figure 1. At arc excitation (U_a = 30 – 31 V, I_a = 120 – 150 A), in addition to arc column (core) *3*, also the presence of plume *4* was found between electrodes *1* and *2*, the plume length being 25 to 30 mm, with the arc column length smaller by an order of magnitude.

The arc column separation into the core and the plume is described in detail in [5, 6] where it is demonstrated that the flow velocities in the core are by an order of magnitude higher than in the plume, while the plume itself is more mobile than the core. Both were located between the electrodes. In the experiments performed by the authors, when the arc ran between graphite electrodes, the plume did not coincide with its core, but propagated from the cathode area into space (Figure 1). A photo of the arc taken through dark glass, confirms the presence of such a plume (Figure 2).

Electric probing of the plume was performed to establish its nature. Used as probes *5* (Figure 1) was nichrome wire of 0.8 mm diameter. Potential distribution was measured with voltmeters *PV1* – *PV3*. It was found that potential difference along plume length $U_{PV1} = 0$, between the plume and anode U_{PV2} = = 25 – 26 V, and that between the plume and cathode $U_{PV3} \approx 6$ V. When the arc voltage was changed from 30 to 50 V the above cathode voltage varied in the range of 6 – 8 V. Voltage U_{PV3}, probably, corresponds to cathode voltage drop.

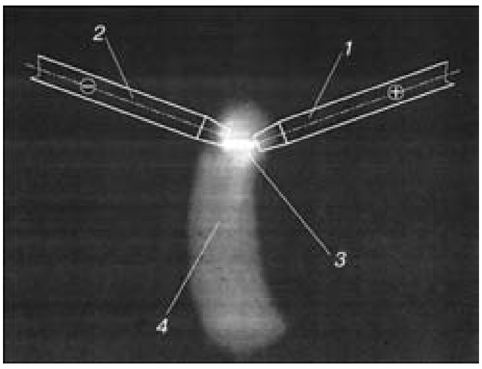

Figure 2. Electric arc running between graphite electrodes (same designations as in Figure 1)

If such a plume exists in SAW and has sufficient energy potential, it can also contribute to flux melting. Presence of a plume in arc welding, breaking through the flux, in the weld pool tail part, is noted in [7, 8].

The following experiment was conducted to evaluate the energy characteristics of the arc plume. Copper plate *1* (Figure 3) of 176.6 g weight and 9.5 × 30 × × 68 mm size, located in metal casing *2* and thermally insulated from it and the environment by asbestos insert *3*, was placed for a fixed time interval (5 – 6 s) under arc plume *4* at approximately 5 mm distance from its core *5*. Energy parameters of the arc were as follows: U_a = 30 V, I_a = 100 A. Plume *4* touched plate *1*. After this time interval was over, the plate was quickly removed from under the plume and covered with a heat-insulating cover. After temperature equalising through the entire volume of the plate, it was recorded using thermocouple *6* and instrument *7*.

Heat capacity of a substance is described by expression $c = Q/(M)\Delta T$ [9], where Q is the amount of heat, kJ; M is the weight of the body being heated, kg; ΔT is the change of temperature of the body being heated, K. Knowing that for copper c = = 0.39 J/(kg·K), we can calculate the amount of heat consumed for increase of the copper plate temperature, which was 4.0 – 4.2 kJ in the performed experiments. With the arc power equal to 3 kW, and arcing time of 5 – 6 s, the amount of energy evolved in it was 15 – 18 kJ. Thus, the energy concentrated in the plume, is equal to about 20 – 25 % of the energy consumed in arcing, this being indicative of a sufficiently high thermal effectiveness of this component of the arc welding process.

When the arc runs above the flux, its heating is due to radiation of the arc and its plume. Under a layer of flux the direct impact of the arc column (core) on the flux is added to these factors.

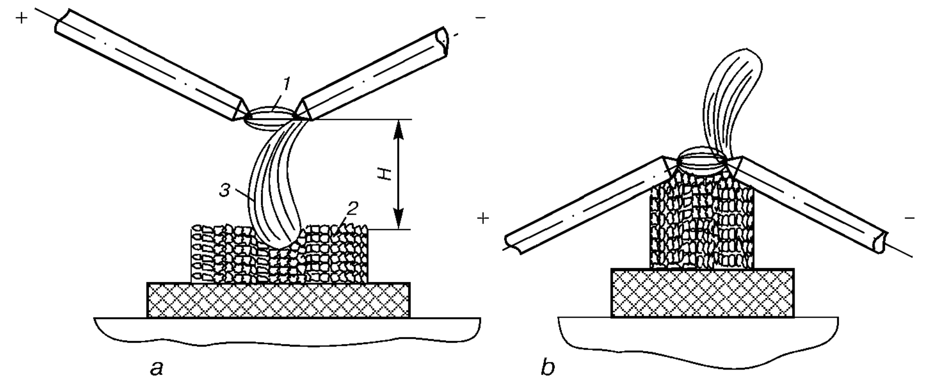

Figure 4. Schematics of flux melting by the arc (for designations see the text)

Experiments, implementing the schematics given in Figure 4, were conducted to determine the direct impact of the arc core and plume on the flux. Arc *1* was ignited above flux *2* (Figure 4, *a*) and plume *3* was brought into contact with its surface with the stationary heat source. Here, distance H from flux surface to arc core was 3 mm. The plume intensively melted the flux, also making a physical impact on the liquid slag. Under this impact the slag pool was observed to form flows that, entraining new flux portions from the periphery, transported them to the center, as well as in depth of the molten slag region. Therefore, the flows formed in welding do not only transfer the heat, but also transport the flux, thus entraining new portions of it into the reaction zone and intensifying its melting.

Next experiments on flux melting were performed with a moving arc. The speed of its displacement relative to the flux was 30 m/h, while the vector of the displacement speed (except for specially mentioned cases) was directed along a normal to the drawing plane (Figure 4). Distance H from flux surface to the arc was varied during the experiments, with the arc located above its surface and under the flux. Duration of arc displacement (arcing) was 10 s in all the experiments. After completion of the experiment, the flux solidified after melting, was weighed. Experimental results are given in Figure 5, from which it follows that with the arc located above the flux, i.e. at positive values H the nature of flux melting by plume *3* (see Figure 4, *a*) is non-linear with the change of this value. When the arc is located directly near the flux, its melting intensity q is maximum but it quickly drops with the increase of distance H. Solidifying flux forms a continuous bead. When H is changed from 2.5 to 10.0 mm, the intensity of the flux melting, dropping practically two times, compared to the previous section, is stabilised at the level of 0.5 g/s. Solidifying slag forms a discontinuous bead, consisting of long fragments. With further increase of distance H the intensity of flux melting abruptly drops again, and then it remains constant in the range of 15 to 22 mm. Slag is formed of individual solidified fragments.

When the arc is lowered under a layer of flux (negative values of H in Figure 5), all the energy factors of the arc contribute to its melting to the utmost. Melting intensity q also rises, accordingly, increasing practically two times, compared to the case of the arc displacement above the flux in the immediate vicinity of its surface. Slag forms a continuous bead.

Energy component of flux heating, related to arc radiation, can be separated at displacement of the latter above the flux, according to Figure 4, *b*. Arc plume is directed upwards and makes practically no contribution to flux heating. Implementation of such an experiment demonstrated that the flux is practically not melted by the arc radiation (in Figure 5 this q value is denoted by a light square). Just individual grains are melted, that probably were directly in the zone of the arc column.

Study [10] presents a model of flux melting that consists in arc column introduction into it with the welding machine displacement with the welding speed. Flux is «pumped» through the arc and melted. The role of this factor in flux melting can be revealed by decreasing the intensity of «pumping» through the arc core. For this purpose, arc displacement in the direction of vectors $\mathbf{v}_{w1}$ and $\mathbf{v}_{w2}$ was provided when the arc ran under a layer of flux (see Figure 1). Graphite electrode moving ahead of the arc (anode in the first case and cathode in the second case) drives the flux to the sides, thus shielding the arc core from the immediate penetration of new flux portions into this zone. Experimental results are given in Figure 5, designated by circles (light for the first case, and dark for the second). The Figure shows that the intensity

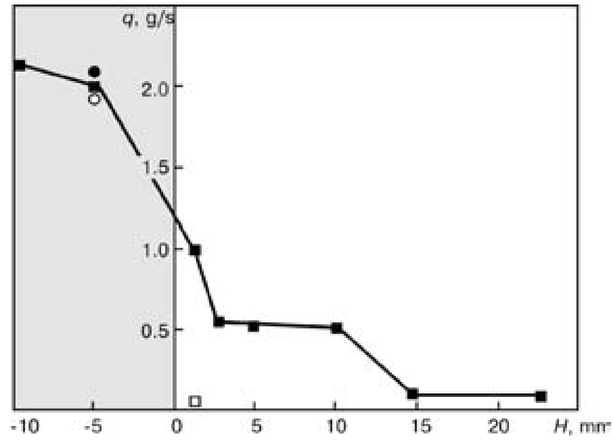

Figure 5. Change of the intensity of flux melting by the arc

of flux melting remained practically unchanged. The reason for that can be the arc core surface smaller than that of the plume, that can interact with the flux, when the arc moves in it. Therefore, the contribution of the arc core to flux melting is also small.

Under the actual conditions of SAW, the length of the arc column, calculated using the data on voltage drop in the near-electrode regions and its distribution in the arc column [11] is equal to just 1.5 – 2.5 mm for U_a = 30 – 32 V and agglomerated fluxes AN-348A (SiO_2 — 41 – 44; MnO — 34 – 38; MgO — 5.0 – 7.5; CaF_2 — 4.0 – 5.5 wt.%), OSTs-45 (SiO_2 — 38 – 44; MnO — 38 – 44; CaF_2 — 6 – 9 wt.%). With such a length of the arc and wire electrode diameter of 4 – 5 mm, the contribution of the arc column radiation to the flux melting and flux «pumping» through it cannot be significant.

CONCLUSIONS

1. Contribution of arc column radiation to flux melting is insignificant.

2. In an arc running between graphite electrodes a plume is formed, its energy potential being sufficient for intensive melting of the flux.

3. Intensity of flux melting is determined not only by the thermal effect of the plume, but also by its physical impact that results in formation of flows in the slag, transferring the heat from the energy source to peripheral zones.

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AUTOMATED THERMAL SPRAYING LINE FOR APPLICATION OF ANTICORROSION COATINGS ON TUBULAR METAL STRUCTURES AND PIPES

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ABSTRACT

The paper describes an automated thermal spraying line that has been developed for application of anticorrosion coatings on tubular metal structures and pipes. Ingenuous technical solutions incorporated into the line design, allow solving in practice the issues of automated application of coatings by electric arc metallising, ensuring high quality of the products.

Key words: *automated line, electric arc metallising, anticorrosion coatings*

Prevention of metal corrosion is one of urgent problems in modern fabrication. Absence of sufficiently resistant materials or effective anticorrosion means often turns out to be a serious obstacle for further progress of science and technology, being highly detrimental to the economy and the tempo of its development.

A tendency of extensive use of thermal coatings as an effective means of metal protection from corrosion damage was observed over the last years. Applying thermal coatings on the surface of metal structures, pipelines, engineering facilities, parts of machinery and mechanisms provides corrosion protection for the term of up to 20 – 30 years.

In Ukraine, an electric arc coating process is becoming widely accepted. The process consists in electrode metal melting by the heat of the electric arc, its dispersion by a high-speed gas flow and deposition of the sprayed particles on a prepared surface.

The main advantages of this process consist in a high efficiency and cost-effectiveness, in addition to a higher quality of the sprayed coating structure (in terms of corrosion attack resistance), simplicity and adaptability of the used equipment to fabrication.

A factor restraining a wider introduction of electric arc metallising process, however, is the absence of the means of integrated mechanisation and automation, allowing a considerable increase of the coating

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application efficiency, reducing the labour consumption and coating cost. It is obvious that development and introduction of such production facilities is of a certain practical interest and of great importance for the national economy.

PSTU developed an automated line [1], designed for application of anticorrosion aluminium and zinc coatings on tubular metal structures and pipes of 50 to 90 mm diameter, the capacity of which is 3000 m per day with three-shift operation. The line (see the Figure) allows applying 0.2 – 0.3 mm thick coating in the automatic mode. It consists of loading rack *3* with magazine-accumulator for piece-by-piece feeding *5* of tubular billets, block of roller-type conveyors *6*, grit-blasting *7* and electric arc metallising *9* chambers of continuous-operation type, sprayed pipe discharge mechanism *14* and take up magazine for finished products *13*.

The line operates as follows. A pack of pipes is placed into the loading rack, from where the pipes are fed piece-by-piece along an inclined slide by a pneumatically-driven lever mechanism to the transporting roller-type conveyor that is a special feature of this line.

The existing units incorporate different principles of the sprayed part displacement, that can be divided into three variants. The first uses the lathe principle — one tubular billet is placed into the rotator, and the metallising unit, mounted on a carriage, moves along the part being sprayed. The disadvantages of such a schematic are obvious, consisting in the absence of the means of integrated automation, and, consequently, in a considerable labour consumption and low efficiency of the process. In the second variant, the device, providing displacement of the sprayed part, is a pushing carriage-rotator. Both its design and feed drive, are rather complicated and poorly adapted to fabrication, whereas the process of loading in the tubular billet proper, is labour-consuming. And, finally, the third variant, arranged as a production line, even though it is fitted with driven idlers, still provides a single-line flow of the pipes being sprayed, thus restraining the increase of product output.

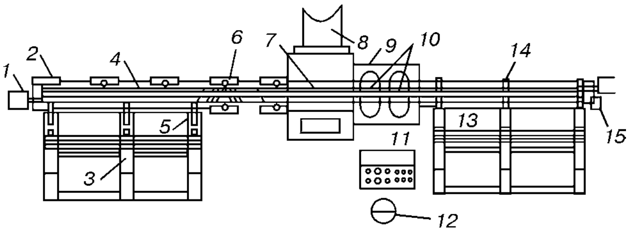
The design of the developed automated line takes into account all the above disadvantages and implements ingenuous approaches to their elimination.

The main working element of the line transporting system is a block of roller-type conveyors, allowing two pipes to be processed simultaneously, i.e. a two-line feed system was applied, that drastically increased the line efficiency.

Line specification

Capacity per shift, m	1000
Coating thickness, mm	0.2 – 0.3
Operational mode	three-shift
Servicing personnel, pers.	3
Pipe length, m	6 – 12
Pipe feed rate, m/min	0.47 – 1.80
Overall dimensions, m	25 × 10 × 10

The block of roller-type conveyors consists of a system of idlers (driving and driven) imparting translational-rotary motion to the workpieces being sprayed, and the driving mechanism allows controlling the pipe movement speed in a broad range.



Schematic of an automated thermal straying line for applying anticorrosion coatings on tubular metal structures and pipes: *1* — transporting roller-type conveyor drive; *2* — side floating support; *3* — loading rack; *4* — item being sprayed; *5* — magazine-accumulator for piece-by-piece feeding of items; *6* — two-line block of roller-type conveyors; *7* — grit-blasting chamber; *8* — air-cleaning equipment; *9* — electric metallising chamber; *10* — electric metallising units; *11* — control panel; *12* — operator's workplace; *13* — take-up magazine for finished products; *14* — sprayed item discharge mechanism; *15* — limit switch of roller conveyor drive

The block of synchronising the pipe motion, practically eliminating disbalanced feed of both workpieces that has been used for the first time in lines for such an application, is of certain interest. Moving along the line, the pipes come to the grit-blasting chamber, where their outer surface is cleaned to remove contamination, layers of scale and rust, oxide films, as well as provide the required roughness of the surface being sprayed. Cast iron spheres of 0.8 to 1.6 mm diameter are used as the abrasive material.

After cleaning, the pipes are fed into the arc metallising chamber, where an anticorrosion coating (zinc or aluminium) 0.2 – 0.3 mm thick is sprayed onto their surface. The chamber is fitted with two upgraded highly efficient arc metallising units. The essence of the upgrade consists in the use of a new spraying head [2], fitted with two additional nozzles, in addition to the central one. The superesonic jets, generated by them, form a gas flow. Gas-dynamic characteristics of this flow create a lower pressure zone in the electrode contact point. Maximal use of the incident flow energy and lowering of its turbulence result in a higher effectiveness of molten electrode metal removal. Under the impact of the growing aerodynamic force, the molten metal is intensively removed, improving heat transfer from the arc active spots to the electrodes, thus promoting a higher efficiency of the metallising process. Therefore, the particle size distribution in an air-metal jet becomes more uniform and finely-dispersed (~50 – 70 μm), thus improving the adhesion strength and lowering the porosity in the deposited coating. The coefficient of electrode metal utilisation also markedly increases.

Coated pipes are unloaded from the transporting roller-type conveyor by the pneumatically-driven discharge mechanism and are transferred to the take-up magazine.

During cleaning and metallising the metal dust is collected by wet cleaning filters. The equipment operation is controlled and monitored automatically from the control panel.

When the line was developed, the issues of automated deposition of metallising coatings on tubular metal structures and pipes have been solved for the first time in local practice. A significant saving of production areas has been achieved, compared to lacquer-paint application and electroplating processes for corrosion protection. The products made fully meet the standard requirements to the appropriate items.

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PARAMETERS OF A DEVICE PROVIDING LONGITUDINAL OSCILLATION OF THE ELECTRODE WIRE TIP

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ABSTRACT

A mechanism providing pulsed wire feed in mechanised welding is proposed. Analysis of the pulsed feed mechanism transmission ratio has been performed, allowing its optimal design parameters to be determined.

Key words: *pulsed feed mechanism, analysis, amplitude, longitudinal displacements, transverse displacements*

The main disadvantage of consumable electrode CO_2 arc welding is higher spatter of electrode metal and unsatisfactory formation of welds. Studies [1 – 4] established the possibility of a considerable enhancement of the process properties of arc welding and surfacing, using the mechanisms of pulsed feed of electrode wire. However, alongside the high potential of the above process, a low reliability of the pulsed electrode feed mechanisms is noted, that is attributable to the presence of one-sided grips in their design [3]. This disadvantage is not present in the feed mechanism, based on a quasiwave transducer [4].

In mechanised welding, a considerable distortion of the generated pulse parameters in the flexible guide is found. Reduction of the feed pulse amplitude is equal to 30 – 35 % of its value at the guide inlet [5]. In view of the above, obvious is the need to place the mechanism of longitudinal oscillation transformation as close as possible to the electrode tip, in order to shorten the welding torch guide length. It is readily implemented in automated welding, where the feed mechanism is located directly in front of the welding torch. In mechanised welding the mechanism of longitudinal oscillations is mounted in the torch holder of the semi-automatic machine, thus greatly increas-

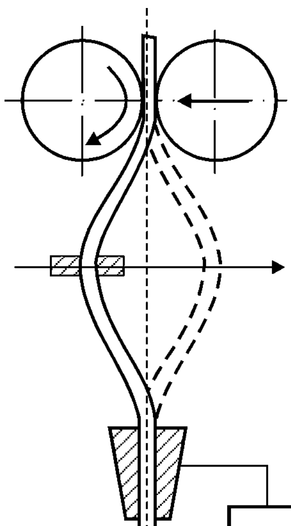

Figure 1. Schematic of the mechanism transforming transverse oscillations of the electrode into longitudinal oscillations: PS — power source

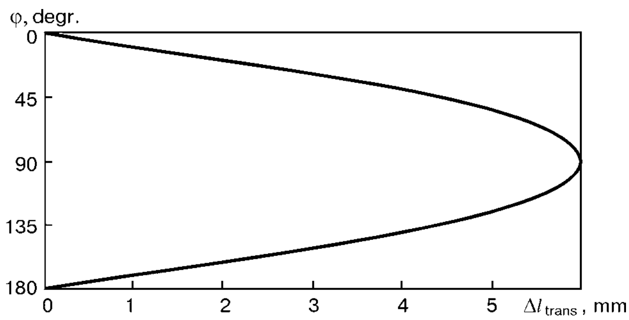

Figure 2. Curve of transverse oscillations of the central part of electrode section: φ — the angle of cam rotation, Δl_{trans} — amplitude of transverse oscillations of the electrode

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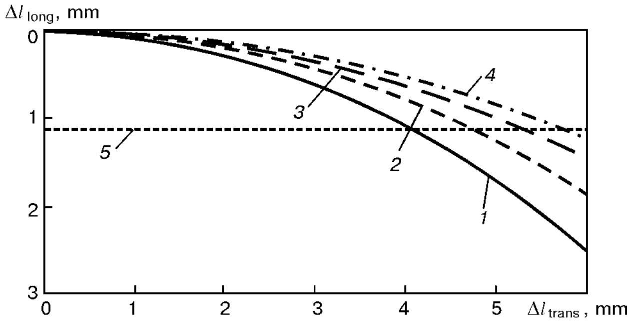

Figure 3. Dependence of longitudinal displacements Δl_{long} of the electrode tip on the amplitude of its transverse displacements Δl_{trans} at different radii of the units: *1 – 4* — unit radius of 15, 20, 25 and 30 mm, respectively; *5* — averaged arc length

ing its weight and impairing the welder's working conditions.

The known mechanisms of pulsed feed of the electrode wire were the basis to develop an improved device [6], that transforms the electrode transverse oscillations into longitudinal oscillations. Its design features allow varying in a broad range the geometrical parameters, and, hence, also the weight of the feed mechanism, depending on the required power of the electric motor. Analysis of the conditions of operation of a mechanism, transforming transverse oscillations of the electrode into longitudinal oscillations, has been performed to optimize the above parameters.

In the considered variant, the functions of the units of pulsed electrode wire feed mechanism are fulfilled by a section of the electrode wire located between the feed roller and sliding current conduit (Figure 1). Transverse displacements of the central part of the electrode section follow the sinusoidal law with adjustable amplitude (Figure 2). Dependence of longitudinal displacements of the electrode tip on the amplitude of its transverse displacements at different radii (15, 20, 25 and 30 mm) of the units is shown in Figure 3. From the above data it follows that the transmission ratio of the mechanisms, transforming the longitudinal/transverse oscillations, $\Delta l_{long}/\Delta l_{trans}$, increases with the reduction of the unit radius. A too great decrease of the unit radii, however, can lead to residual deformation of the welding wire. The transmission ratio becomes higher with the increase of the transverse displacement amplitude. This means that transverse displacements with low amplitudes are inefficient. So, at 4 mm amplitude, longitudinal displacement is equal to 1.2 mm. When the amplitude varies between 4.0 and 5.5 mm, it is still equal to 1.2 mm, as the transmission ratio is close to a unity, being 1.2 mm/1.5 mm.

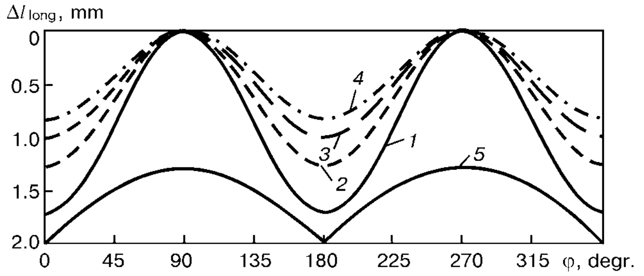

Figure 4. Curves of longitudinal displacements of electrode tip, depending on unit radius and angle of cam rotation: *5* — power source voltage (designations *1 – 4* see in Figure 3)

Transverse displacement amplitude of 4.0 to 5.5 mm should be used to increase the reliability of the mechanism, transforming transverse oscillations into longitudinal oscillations. Under such conditions, the electrode tip oscillates by a sinusoidal law (Figure 4) with double (100 Hz) frequency. To make the electrode tip more abruptly approach the weld pool, it is rational to use a cam mechanism with 1.5 mm amplitude of longitudinal oscillation. In order to ensure the feed rate of 100 pps, when using a synchronous motor with the rotation frequency of 3000 rpm, it is necessary to place two cams along the length of the circumference. The moment of pulsed feed of electrode wire can be synchronised with the moment of voltage drop in the power source of a full-wave single-phase welding rectifier.

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MINIMIZING THE LOSS OF METAL DEPOSITED USING A FLUX-CORED STRIP

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ABSTRACT

Conditions of arc surfacing with a strip are discussed under which the metal loss during subsequent machining is minimal.

Key words: *surfacing, machining, minimal metal loss, bead parameters, flux-cored strip*

One of the main conditions of an optimal process of arc surfacing with a flux-cored strip, is selection of deposited bead geometry, that ensures minimal metal loss in subsequent machining.

The purpose of this work is to find the conditions under which the deposited metal loss after finish turning of the deposited body will be minimal (hence, the cross-sectional area of bead reinforcement after turning should be maximal). From the cross-section of beads deposited using a flux-cored strip, one can see that the cross-sectional shape of the deposited bead reinforcement can be assumed to have the shape of a rectangle, rounded off by an arc of a circumference of radius h_1 (height of bead reinforcement) (Figure 1), while the cross-sectional shape of the base metal penetration can be taken to be a parabola, plotted from the following equation:

$$y = \frac{4h_2}{b^2} x^2 - h_2,$$

where h_2 is the penetration depth; b is the width of the deposited bead.

Let us find the length of section MC which will exactly be the thickness of the deposited layer after turning. Let ωh_1 denote $H/2 - (b/2 - h_1)$. Then, the factor is

$$\omega = \frac{H - b + 2h_1}{2h_1}, \quad (1)$$

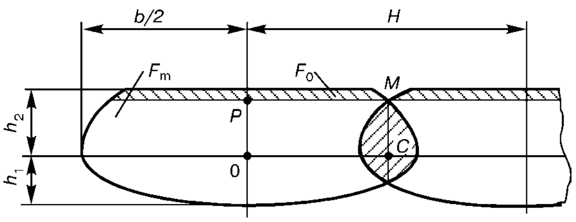

Figure 1. Calculation of parameters of a bead deposited with flux-cored wire (for designations see the text)

where H is the surfacing pitch.

We have

$$MC = \sqrt{h_1^2 - (\omega h_1)^2} = h_1 \sqrt{1 - \omega^2}. \quad (2)$$

Let us denote the relative surfacing pitch H/b as α, and value h_1/b as p. Then, factor ω can be expressed through α and p as follows:

$$\omega = \frac{b}{2h_1}\left(\frac{H}{b} - 1 + 2\frac{h_1}{b}\right) = \frac{\alpha + 2p - 1}{2p}, \quad (3)$$

and the area of bead reinforcement after turning will be equal to

$$F_m = 2F_{OPMC} = Hh_1\sqrt{1 - \omega^2} = h_1 b\alpha \sqrt{1 - \omega^2} = b^2 p\alpha \sqrt{1 - \omega^2}. \quad (4)$$

If turning of the deposited bead is not performed, then, as follows from Figure 1 and equation (4), bead reinforcement area will be maximal at $\omega = 0$ and equal to $b^2 p\alpha$. From (3) it follows that

$$\alpha = 1 - 2p, \quad (5)$$

while the area of the deposited bead reinforcement is equal to

$$F_m = b^2 p\,(1 - 2p). \quad (6)$$

In order to find the maximum of function (6), let us find its derivative with respect to p and setting it equal to zero, we will have

$$(p - 2p^2)' = 1 - 4p = 0, \quad p = 0.25.$$

Thus, if turning of the deposited bead is not performed, surfacing with a flux-cored strip must be conducted in the modes, providing $p = h_1/b = 0.25$. In this case, $\alpha = 0.5$.

In practice, value $p = 0.25$ is usually not achieved. However, if turning of the deposited bead is not performed, in this case it is still recommended to conduct surfacing with relative pitch α, its values being selected from equation (5).

In order to achieve the maximal cross-sectional area of the bead reinforcement after finish turning (in the case, if machining is performed), let us find the maximum of function (4) with respect to variable α. For this purpose, let us find its derivative, considering that parameter ω also is a function of α, then

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Optimal values of relative surfacing pitch α

p	Calculation by equation	
	(5)	(7)
0.05	0.9	0.911
0.10	0.8	0.845
0.15	0.7	0.800
0.20	0.6	0.770
0.25	0.5	0.750
0.30	0.4	0.736
0.35	0.3	0.726
0.40	0.2	0.718

$$(\alpha \sqrt{1-\omega^2})' = \sqrt{1-\omega^2} + \alpha\ (\sqrt{1-\omega^2})' =$$

$$= \sqrt{1-\omega^2} + \frac{\alpha}{2\sqrt{1-\omega^2}}(-2\omega)\,\omega' =$$

$$= \sqrt{1-\omega^2} - \frac{\alpha\omega\omega'}{\sqrt{1-\omega^2}} = \frac{1-\omega^2-\alpha\omega\omega'}{\sqrt{1-\omega^2}}.$$

Finally, we will have equation

$$1 - \omega^2 - \alpha\omega\omega' = 0.$$

Substituting expression (3) instead of ω, we obtain

$$1 - \left(\frac{\alpha + 2p - 1}{2p}\right)^2 - \alpha\,\frac{\alpha + 2p - 1}{2p}\,\frac{1}{2p} = 0.$$

After conversion of this expression, we will have a quadratic equation

$$2\alpha^2 + (6p - 3)\,\alpha + (1 - 4p) = 0,$$

solving which gives us

$$\alpha = \frac{-(6p-3) \pm \sqrt{(6p-3)^2 - 4\cdot 2\,(1-4p)}}{4} =$$

$$= \frac{3 - 6p \pm \sqrt{36p^2 - 4p + 1}}{4}.$$

Analysis of this solution showed the need to take a greater root. Then, the optimal value of the relative surfacing pitch will be

$$\alpha = 0.75 - 1.5p + 0.25\sqrt{36p^2 - 4p + 1}. \qquad (7)$$

The Table gives the optimal values of pitch α of flux-cored strip surfacing for two variants: when turning of the deposited metal is not performed and when it is performed.

Figure 2 shows the dependence of the cross-sectional area of bead reinforcement after machining F_m on relative surfacing pitch α and bead parameter p. It is seen that the maximal area F_m is achieved at values α, calculated from equation (7).

With the change of values α from 0 to $(1 - 2p)$, area F_m grows linearly according to expression $b^2p\alpha$. With further increase of pitch α, change of values F_m occurs non-linearly, according to equation (4).

Let us find the area of the deposited bead reinforcement cross-section, removed in finish turning. Based on Figure 1, we have

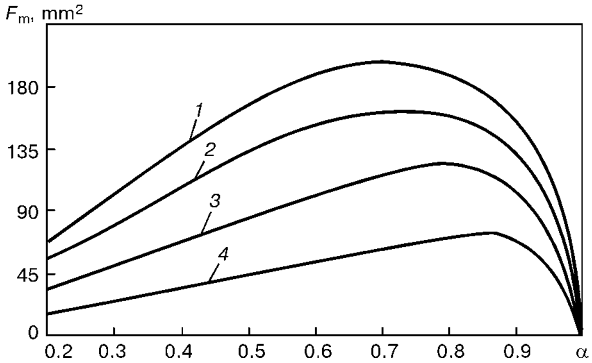

Figure 2. Dependence of area F_m on α and p at b = 30 mm: *1* — p = 0.4; *2* — p = 0.3; *3* — p = 0.9; *4* — p = 0.1

$$F_0 = 2(h_1 - MC)\,(H/2 - \omega h_1) + 2\int_0^{\omega h_1}(\sqrt{h_1^2 - x^2} - MC)\,dx =$$

$$= (h_1H - 2h_1^2\omega)\,(1 - \sqrt{1-\omega^2}) + h_1^2 \arcsin\omega +$$

$$+ h_1^2\omega\sqrt{1-\omega^2} - 2h_1^2\omega\sqrt{1-\omega^2}.$$

Proceeding from relationships $H = b\alpha$ and $h_1 = bp$, we will have

$$F_0 = (b^2\alpha p - 2b^2p^2\omega)\,(1 - \sqrt{1-\omega^2}) +$$

$$+ b^2p^2\,(\arcsin\omega - \omega\sqrt{1-\omega^2}) =$$

$$= b^2p\,[(\alpha - 2p\omega)\,(1 - \sqrt{1-\omega^2}) + \qquad (8)$$

$$+ p\,(\arcsin\omega - \omega\sqrt{1-\omega^2})].$$

From (8), it is seen that if $\omega = 0$, then $F_0 = 0$, i.e. deposited metal turning in this case is not performed and no metal is removed.

Let us find the proportion of the remaining metal after turning:

$$\gamma = \frac{F_m}{F_m + F_0}.$$

We have

$$F_m + F_0 = b^2p\alpha\sqrt{1-\omega^2} + b^2p\,[\alpha\,(1 - \sqrt{1-\omega^2}) -$$

$$- 2p\omega + 2p\omega\sqrt{1-\omega^2} + p\arcsin\omega - p\omega\sqrt{1-\omega^2}] =$$

$$= b^2p\,(\alpha - 2p\omega + p\omega\sqrt{1-\omega^2} + p\arcsin\omega).$$

Hence,

$$\gamma = \frac{\alpha\sqrt{1-\omega^2}}{\alpha + p\,(\arcsin\omega + \omega\sqrt{1-\omega^2} - 2\omega)}. \qquad (9)$$

With the increase of relative surfacing pitch, α, the proportion of metal remaining after turning, γ, becomes smaller. For large values of p parameter, values of parameter γ are smaller.

Thus, the found dependencies of parameters of the deposited layer of flux-cored strip, allowed determining the conditions under which the amount of the deposited layer metal, removed in final turning, is minimal.

MANGANESE-CONTAINING SURFACING CONSUMABLES

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ABSTRACT

Results of the work performed at the Priazovsky State Technical University on making surfacing consumables to provide the deposited layer with meta-stable austenite reinforced with hardening phases and realize the effect of self-hardening under loading are generalized. The above effect is caused by transformation of austenite into martensite under loading during the wearing process.

Key words: *flux-cored strip, deposited metal, martensite, meta-stable austenite, wear resistance, carbides, carbonitrides*

One of the advanced areas in welding industry is development of materials with a meta-stable structure, which are capable of self-adapting under the external effects [1]. Such materials called «smart» and «adaptable» include steels, cast irons and surfacing consumables on their base. They provide a structure with meta-stable austenite which undergoes martensitic transformations (the self-hardening effect under loading). The idea of making such alloys for parts subjected to cavitation fracture was put forward by I.N. Bogachev and R.I. Mints [2]. They developed steel 30Kh10G10 (chemical composition of the materials mentioned is given in Table 3), while the S.M. Kirov branch laboratory of the Ukrainian Priazovsky Institute developed wire Np-25Kh10G10T intended for surfacing of crane wheels, plungers of hydraulic presses, buggy rollers, etc. However, metal deposited with such a wire is hard to process by cutting because of a low stability of austenite. Besides, it has an insufficient corrosion resistance because of a comparatively low chromium content. Therefore, surfacing should be performed by a special technology to retain the austenitic structure of the deposited metal.

To improve workability by cutting, it is expedient to use consumables which provide the deposited metal with a decreased carbon content (≤ 0.2 %) and increased stability of austenite. In this case an increase in wear resistance is achieved by reinforcing austenite with carbides or carbonitrides of elements of groups IV and V of the Mendeleev's system. The level of stability of austenite and the amount of the hardening phase are regulated depending upon the service conditions and requirements for mechanical properties. This can be achieved by changing the content of carbon (0.08 – 0.16 %), nitrogen (0.05 – 0.15 %), carbide- and nitride-forming elements, such as vanadium (0.05 – 1.00 %) combined with chromium (13 – 14 %) and manganese (10 – 14 %).

An important peculiarity of this type of the deposited metal is that heat treatment, which is normally conducted to relieve internal stresses after surfacing (600 – 650 °C), provides precipitation of dispersed phases in austenite of the deposited metal, which results in its destabilization and martensitic transformations under loading during operation. By varying heat treatment conditions, it is possible to regulate deformation martensitic transformations over wide ranges.

This principle was used as a basis for development, in collaboration with the OJSC «Azovmach», of flux-cored strips PL-Np-15Kh13AG10MFS [3], PL-Np-25Kh1410F [4] and PL-Np-20G14AF [5], and in collaboration with UkrNIISpetsstal — solid wire Sv-14Kh14G12F [6]. Investigations described in [7] showed that the intensive deformation martensitic transformation plays a fundamental role in increasing wear resistance under sliding friction conditions at relatively low velocities (0.13 m/s) and absence of or low preheating of the rubbing surfaces. In the case of tests performed at an increased sliding velocity (0.98 m/s) the intensity of the martensitic transformation in friction decreases due to an increase in temperature of the working surface. Under such conditions wear resistance of the deposited metal is determined by the hardening ability of austenite. The latter depends upon the carbon content, which is confirmed by the data given in Table 1.

Wear resistance tests under rolling friction conditions (pressure 320 MPa, frequency of rotation of rollers 0.98 m/s, frequency of slip 0.09 m/s) showed that deposited metal with an intensive deformation martensitic transformation is characterized by a higher wear resistance. Thus, with this test method the deposited metal of the 15Kh13AG10MFS type contains ≈35 % and that of the 20Kh13AG10MFS type contains ≈23 % of deformation martensite, and in the first case the relative wear resistance is 6.2 and in the second case — 5.8. Metal deposited with the Sv-30KhGSA type wire was used as a reference.

The temperature of heating of the deposited metal in heat treatment (450 – 650 °C) performed in order to decrease internal stresses has a definite effect on its wear resistance. As shown by the tests conducted

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under sliding friction (relatively low velocities) and rolling friction conditions, heating to 450 °C (1 h) decreases wear resistance of the deposited metal approximately by 30 %, whereas heating to 650 °C increases it approximately by 40 %, as compared with the quenched state. This is caused by the fact that in the first case austenite is stabilized with regard to the deformation martensitic transformation, and in the second case it is destabilized because of precipitation of carbides and carbonitrides. In the latter case the positive effect is exerted by dispersed particles of the precipitated phases. Under friction conditions which do not lead to a substantial preheating of the surfaces in contact, preliminary cold plastic deformation increases wear resistance of the deposited metal due to activation of the deformation martensitic transformation. Thus, a 10 % deformation resulted in a doubled wear resistance of the deposited metal of the 15Kh13AG10MFS type. A still larger effect is provided by a combined treatment, including cold plastic deformation and subsequent heating which causes precipitation hardening of the formed martensite and austenite. In this case wear resistance of the deposited metal increases almost three times.

Under conditions of friction accompanied by a considerable increase in temperature (over 450 °C), preliminary cold deformation decreases wear resistance of the deposited metal. This is caused by transformation of martensite formed during deformation into austenite, which leads to a decrease in plastic deformation resistance of the metal. Surfacing by the SAW method using the developed flux-cored strips with a cross section of 20 × 4 mm and fluxes of the AN-348A (SiO_2 — 41 – 44; MnO — 34 – 38; MgO — 5.0 – 7.5; CaF_2 — 4.0 – 5.5 wt.%), OSTs-45 (SiO_2 — 38 – 44; MnO — 38 – 44; CaF_2 — 6 – 9 wt.%) and AN-60 (SiO_2 — 42.5 – 46.5; MnO — 37 – 41; CaO — 3 – 11; MgO — 0.5 – 3.0; CaF_2 — 5 – 8 wt.%) grades is performed under the following conditions: I_w = = 600 – 650 A, U_a = 30 – 32 V, v_w = 35 m/h. This provides a stable arc burning, good formation of the deposited bead and detachability of the slag crust. The above consumables are intended for wear-resistant surfacing of crane wheels, trunnions of steel casting ladles and hydraulic press plungers, the service life of which is fundamentally extended.

The use of Cr–Mn surfacing consumables is also indicated for some parts operating at temperatures of 600 – 700 °C, which was proved in the case of application of the flux-cored wire of the PP-35ZhN grade, providing the 10Kh13G12AFSYuR type of the deposited metal [8].

Table 2 gives comparative data on wear and heat resistance, as well as hardness of the deposited metal of the 10Kh13G12AFSYuR and 08Kh21N10G6 types

Table 1. Effect of carbon in the deposited metal of the Kh13AG10MFS type on the amount of deformation martensite and relative wear resistance

Carbon content, wt.%	*v* = 0.13 m/s		*v* = 0.98 m/s	
	Content of deformation martensite, %	Relative wear resistance	Content of deformation martensite, %	Relative wear resistance
0.10	28	4.2	10	3.1
0.15	19	3.8	5	4.8
0.20	12	3.3	–	5.5

at 20 and 600 °C. The data obtained indicate that the latter is much inferior to the Ni-free metal [8]. Analysis of resistance of the Pilger mill rolls, which had been surfaced for a long time using the PP-35ZhN grade wire, under the Open Joint-Stock Company «Ilyich Metallurgical Works» conditions showed that their service life increased by a factor of 1.40 – 1.65, as compared with the rolls which were surfaced using the Sv-08Kh21N10G6 wire [8]. Hence, it can be suggested that the use of the Cr–Mn surfacing consumables is effective in terms of extending life of hot deformation tools and parts operating under specific conditions, similar to those of the Pilger mill rolls.

Consumables based on Fe–Mn–Cr–V–C were developed for surfacing of parts operating under abrasive wear conditions. A distinctive feature of these consumables is formation of the deposited metal containing meta-stable austenite (in a number of cases, together with martensite) reinforced with chromium and vanadium carbides. These consumables realize the principle of self-hardening under loading. An example is the flux-cored strip of the PL-Np-(300 – 400)Kh(12 – 15)G4S2F grade, which is intended for use instead of a more expensive strip of the PL-AN-101 (300Kh28N3S3G2) grade.

Studies [9, 10] give results of development of the Cr–Mn surfacing consumables intended for different impact-abrasive conditions, which are characterized by dynamic coefficient K_d [11] determined by the ratio of hardness of a steel 110G13L specimen after wear under certain wear conditions to its initial hardness. This steel is capable of hardening while accumulating the energy of external effects. The level of hardening allows estimation of an integral intensity of the impact-abrasive effect [11]. Investigations were conducted using the method of experimental design for different values of K_d in a range of 1.2 to 3.5. The content of alloying elements in the deposited metal was varied in the following ranges, %: C — 1 – 3, Mn — 2 – 6, Cr — 6 – 12. Vanadium was additionally introduced in some cases.

It is shown that at low values of the dynamic coefficient (K_d = 1.2 – 1.4) the content of carbon in

Table 2. Properties of metal deposited using wires PP-Np-10Kh13G12AFSYuR and Sv-08Kh21N10G6

Type of deposited metal	Wear of deposited metal at 600 °C and pressure of 15 MPa (test time — 1 h), mg	Heat resistance (number of cycles «heating-cooling» to cracking)	Hardness HRB	
			20 °C	600 °C
10Kh13G12AFSYuR	4.2 – 7.4	930 – 1080	100 – 110	80 – 89
08Kh21N10G6	23.9 – 29.7	440 – 620	82 – 88	66 – 73

Table 3.

Materials	*C*	*Cr*	*Mn*	*Ti*	*Mo*	*V*	*Si*	*N*	*Al*	*W*	*Ni*	*Fe*
30Kh10G10	0.3	10	10									Balance
25Kh10G10T	0.25	10	10	0.3								Balance
15Kh13AG10MFS	0.15	13	10		up to 1	up to 1	up to 1	0.2				Balance
25Kh1410F	0.25	14	10			up to 1						Balance
20G14AF	0.2		14			up to 1		0.2				Balance
14Kh14G12F	0.14	14	12			up to 1						Balance
20Kh13AG10MFS	0.20	13	10		up to 1	up to 1	up to 1	0.2				Balance
30KhGSA	0.3	up to 1	up to 1				up to 1					Balance
10Kh13G12AFSYuR	0.1	13	12			up to 1	up to 1	up to 0.2	up to 0.05	up to 0.3		
08Kh21N10G6	0.08	21	6								10	Balance
110G13L	1.1		13									
230Kh12G2	2.3	12	2									
250Kh10G4F3	2.5	10	4			3						Balance
160Kh12G5	1.6	12	5									Balance

the deposited metal should be 2.0 – 2.5, manganese 2 – 3, chromium ≈12 %, and the metal should have mostly the martensitic-carbide structure. For the above conditions it is advisable to use flux-cored strips of the PL-Np-230Kh12G2 and PL-Np-250Kh10G4F3 grades. An increase in the dynamic coefficient should be accompanied by a decrease in the carbon content and by an increase in the manganese content of the deposited metal. Thus, at $K_d = 3.5$, the optimal content of alloying elements in the deposited metal is as follows, %: C — 1.0 – 1.7, Mn — 5 – 6, Cr — 12. In this case it is recommended to use flux-cored strip of the PL-Np-160Kh12G5 grade. With an increase in K_d, it is necessary to increase the content of residual austenite in the deposited metal and increase its stability with regard to the deformation martensitic transformation. It was established that, if after surfacing the structure and phase composition of the deposited metal differ from the optimum, the efficient method to regulate them is normalizing. Its parameters should be selected with allowance for the intensity of the impact-abrasive effect. With an increase in K_d, it is necessary to use increased temperatures of heating for normalizing in order to increase the amount of austenite in the metal structure and degree of its stability. Surfacing with the developed flux-cored strips with a cross section of 20 × 4 mm should be performed by the SAW method using fluxes of the AN-26 grade under the following conditions: I_w = = 600 – 650 A, U_a = 28 – 32 V and v_w = 35 m/h. The above strips are characterized by good welding properties.

Analysis of the given data shows the efficiency of using the Mn-containing surfacing consumables, which provide the deposited metal containing metastable austenite reinforced with hardening phases and realize the self-hardening effect under loading. An important role of the martensitic transformation consists in the fact that a larger portion of the energy of external effects is consumed for its development, while the smaller portion of the energy goes to fracture [12, 13]. This is accompanied not only by hardening, but also by relaxation of micro stresses, which hampers formation and propagation of microcracks [14]. The deformation martensitic transformation can be applied to control variations in chemical composition of the deposited metal or parameters of heat treatment after surfacing, which allows the highest level of wear resistance to be achieved, provided that its development is optimized.

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MANUFACTURE OF SEMICONDUCTING TRANSDUCERS BY ELECTROCHEMICAL WELDING

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ABSTRACT

Issues associated with electrochemical welding of silicon to steels for making units of pressure transducers and other assemblies are considered. Fields of application of the transducers, their design and technological peculiarities are described. Data on welding equipment and ways of its upgrading are presented.

Key words: *solid-state electrochemical welding, units and materials joined, welding equipment, assembly-welding fixture*

Rapid development of electronic and computer industries has been a major precondition of a wide application of automation and monitoring for the most diverse processes used in industry, medicine, research and domestic appliances. However, realization of this precondition largely depends upon the capabilities of devices employed to get information on a parameter or process being monitored. Such devices include primary transducers of non-electrical values, which are based on piezo- and tensoresistive or capacity effects. Widening of the scope of automation has stipulated increasingly stringent requirements imposed on the transducers. The special consideration is given to the following factors: miniaturization (possibility of building-in or integration), low cost (in mass production), mechanical strength and tightness.

The transducers can be used for any kind of measurements of static and dynamic pressure of gases and fluids. They are particularly convenient in such cases where, along with indication, it is desirable or necessary to record the type of a signal or process it. These measurement devices are widely applied now in different engineering fields: oceanography — for measurement of the ocean depth and wave pressure; machine-building — for tribological measurements and monitoring of oil pressure in large plain bearings; manufacturing processes — for registration of pressure and variations in the level of a fluid; hydraulics and pneumatics — for monitoring and regulation of pressure in the hydraulic systems of brakes and railway rolling stock; automotive industry — for measurement of pressure in oil pumps, internal combustion engines and braking systems; rocket engineering — for measurement of pressure in fuel tanks of rockets; aircraft engineering — for measurement of pressure in hydraulic systems and as rate-of-climb meters; and soil mechanics — for measurement of pressure of underground water and investigation of stability of soft ground. The transducers are used in domestic appliances, as well as in medicine for investigation of hemodynamics of eye and adjoining cerebrum sections, diagnostics of speed characteristics of propagation of pulse waves during the heart cycle, volume measurements of blood circulation, etc.

Using this transducer or other in the above fields is determined first of all by its price and efficiency. In commercial application of the above devices the decisive factor is a measurement error which should be 1 – 2 % in process regulation and 2 – 3 % in monitoring. The ratio of prices of the general to special-purpose transducers is 1:100 – 1:1000.

The transducers are made using non-traditional materials (semiconducting materials, glasses, alloys, ceramics, metal alloys) by advanced planar microtechnologies and new joining methods, such as solid-state electrochemical welding (ECW) (Figure 1) [1].

Advantages of this joining method are as follows:

• possibility of directly joining metal or semiconductor to glass or glass ceramics, by avoiding expensive and scarce brazing filler metals based on gold, indium, silver, etc.;

• joining of materials at temperatures lower than brazing temperatures;

• joining of materials in any atmosphere, including air;

• possibility of operating the joints at temperatures close to the welding temperature;

• reduction of the time of welding to several minutes;

• elimination of high specific compression loads;

• possibility of providing reliable, full-strength and tight joints.

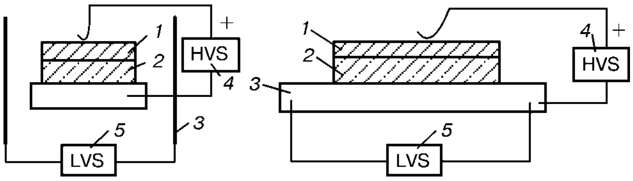

Figure 1. Main flow diagrams of ECW: *1* — glass; *2* — silicon (metal); *3* — heater; *4, 5* — welding voltage (low and high, respectively) sources

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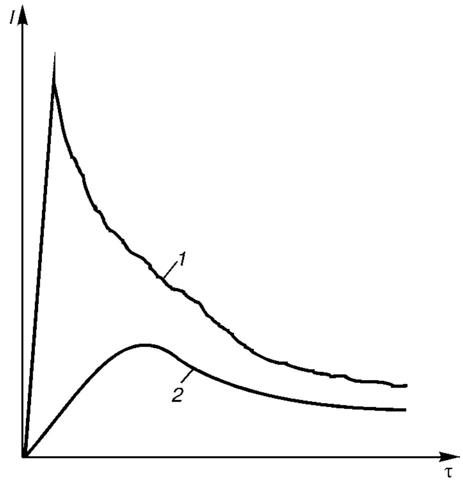

Figure 2. Rigid (*1*) and soft (*2*) ECW conditions

ECW has lately gained acceptance also in the manufacture of planex integrated circuits, gas-discharge instruments and other devices.

An important element of the permanent unit of a transducer is a semiconducting silicon membrane with a tensoresistive bridge or capacitor plate made on one of its surfaces by the planar technology method. In Ukraine and other CIS countries, developers of the transducers use semiconducting elements with geometrical sizes of not less than 3 – 4 mm for making of units of the devices, thus simplifying assembly of the units and design of current-conducting devices. Miniaturization of the transducers, which is one of the requirements for their application in biomedical studies, required some restructuring to be made in design of the assembly-welding fixtures, the current-conducting and heating devices in particular, and correction of welding conditions. Thus, rigid welding conditions are more applicable for making large units. In this case, first an assembly unit is heated to the required temperature and then a welding voltage is supplied. Miniature units require soft welding conditions, under which the parts are heated to the required temperature with the welding voltage switched on (Figure 2). In addition, for miniature parts it is necessary to use a lower welding voltage, differing from the voltage used under rigid welding conditions by

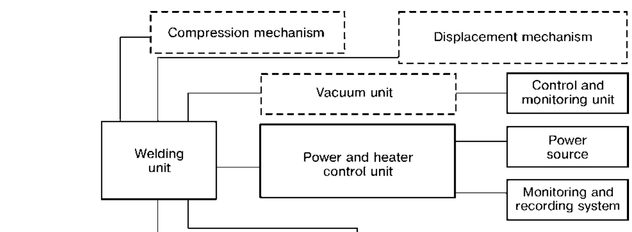

Figure 3. Block diagram of welding installation

an order of magnitude, or increase it gradually in synchronism with a decrease in the welding current.

ECW can be used to join different materials. The Table gives pairs of materials welded, which are widely utilized in units of various-application transducers.

Further development of the technology for the manufacture of welded units is impossible without upgrading of the welding equipment and fixture. This equipment should be characterized by high productivity, in addition to ensuring its main properties, and its assembly should not be labour-consuming, but be performed with a required precision and provide the possibility of evacuating closed cavities of the units and their uniform heating. The issue of labour consumption of the assembly process has been resolved in general due to using replaceable welding fixtures and assembly jigs. The issue of productivity is associated with a method of heating [2]. Here the most difficult problem is to ensure the uniformity of heating of the units. The temperature can be monitored only by a contact method using a limited number of thermocouples, and in practice it can be regulated and maintained by one device.

Our industry does not manufacture installations for ECW of dissimilar materials, while those operating at a number of enterprises were custom made by us. They have a common layout, according to the block diagram shown in Figure 3 (units in dashed boxes are optional). All the installations are based on a welding unit characterized by a high productivity, the possibility of welding in the air atmosphere or in vacuum, versatility as to design peculiarities of parts welded and a heating method. The welding unit operates on a DC high welding voltage supplied from a special power unit which is equipped with a monitoring, recording and control system. The parts are heated by low-voltage heaters. In addition to transformers, the heating unit comprises also the system for monitoring, recording and control of this process. Special-purpose installations have vacuum systems which comprise an evacuation system and system for monitoring and control [3]. Most installations have separate assembly and welding devices, allowing a manual assembly of the parts outside the installation chamber. All the installations are fitted with a manual system for loading and unloading of parts or assembly-welding devices, while some of them are equipped with an automatic welding process control system.

An increasing demand of the industry for the primary information transducers requires solution of the problem of arrangement of their manufacture. At initial stages, allowing for the recent trends, it is necessary to arrange manufacture of the installations with multi-positional assembly-welding devices. However, at this point we may face two negative factors: high labour consumption in assembly and impossibility of monitoring and controlling the welding process. The attempts currently made are aimed at welding non-wafer-separable silicon plates (modules) to glass [4].

List of materials welded and their welding conditions

Material	*Glass grade*	*i*, $\mu A/mm^2$	τ, *min*	*T*, °*C*
Kovar (29NK)	S48-1, S48-2, S52-1	10 – 30	10	500
Molybdenum	S48-1, S48-2, S52-1	10 – 30	10	500
Titanium	S72-4	25	5	400
Tantalum	S72-4, S93-1	25	5	400
Silicon	Pirex, LK-105, S35-1, S37-2	10 – 40	0.5 – 10.0	300 – 450
Germanium	S48-1, S48-2, S52-1	3	2	450
Aluminium (film)	Quartz, S48-1, S48-2, S52-1, S93-1, S93-2, S90-1	1	1 – 10	400 – 500
Ni–Cr alloy	S35-1, S47-1	1	1 – 10	400 – 500
Quartz through Al, Si	Quartz	10	1 – 5	850
Silicon	Sapphire	1	1	450
Gallium arsenide	S52-1, S48-2	25	5 – 10	450
Palladium	Porcelain	100	5	400
Platinum	S52-1, S48-2, S48-2	5	7	400
Silicon	Quartz	10 – 25	1 – 20	400 – 900

This technology dramatically raises the productivity. At the same time, it involves the problem associated with separation of this assembly: it is necessary to have the cutting methods which would provide a quality surface without any cleavages or cracks. In the future it will be necessary to develop automatic or semiautomatic welding installations with individual welding of units. This applies in particular to semiconducting transducers and other semiconducting devices. Full automation of the welding process involving the chip topology identification method can be provided through detection using a commercial TV camera for the topology of contact pads or reference marks on the chips, followed by comparing the circuit being made with a standard one stored on the computer. In this case, detection can be performed using photo-receiving devices. At the same time, it will be necessary to develop a system for feeding the assembled unit in a pressed condition to the heating zone under the welding electrode.

It should be noted in conclusion that solid-state ECW is an advanced and most suitable method for the manufacture of precision permanent units of different materials, such as glasses, semiconducting materials and metals, for making modern monitoring and control devices, domestic appliances and medical equipment.

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GLOW DISCHARGE AS A HEAT SOURCE FOR BONDING AND BRAZING PROCESSES (REVIEW)

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ABSTRACT

Main results of research and development aimed at improvement and widening of technological capabilities of glow discharge as a heat source for joining processes are presented. Methods which hold promise for increasing stability of glow discharge are described and basic types of power supplies and pieces of equipment are characterized. Technological problems which are successfully solved by glow-discharge bonding and brazing are outlined.

Key words: *diffusion bonding, brazing, glow discharge, stability, power supplies, equipment, application field*

Specific combination of physical-chemical and technological peculiarities of formation of diffusion bonds hampers application of concentrated energy sources and imposes increased requirements for locality and regulation of the intensity of heating using distributed heat sources, their adaptability to heating parts of different configurations and dimensions. Among the energy sources used currently for diffusion bonding (induction, radiation, resistance, etc.), the above requirements are most completely met by a glow discharge burning in inert or reducing gases under a pressure which is lower than the atmospheric one.

Initial attempts of using glow discharge for diffusion bonding and brazing of metals date back to the beginning of the 1960s [1]. The first experiments on brazing of metals [2] and zone refining of silicon [3] using a glow discharge in hydrogen date from the same period. Even the very first studies [4, 5] noted simplicity of equipment, high efficiency and cost effectiveness of the process involved. However, along with favourable properties, the studies performed also revealed different types of instability of the gas-discharge plasma, as well as dependence of the process parameters upon the shape and material of parts, which required investigation into physical-technical peculiarities of the glow-discharge plasma used as an energy source for bonding.

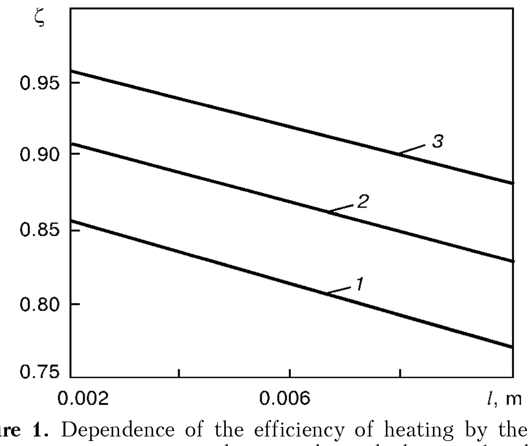

Figure 1. Dependence of the efficiency of heating by the glow discharge in nitrogen upon the inter-electrode distance l under gas pressure p = 2.67 (*1*), 8.00 (*2*) and 13.30 (*3*) kPa

Review [6] published in 1978 and book [7] generalized results of investigations and experience of commercial application of the glow discharge for joining dissimilar metals, alloys and non-metallic materials, considered processes occurring in the medium-pressure gas-discharge plasma, presented characteristics of the equipment developed and showed a promising future of the glow discharge used as a bonding heat source. Later on the main consideration was given to investigation of energy characteristics of the glow discharge under conditions of bonding and brazing, further exploration and expansion of its technological capabilities, in particular, through increasing stability of the discharge under heating conditions varied over wide ranges, as well as to development of new efficient power supplies and building of a high-capacity automated equipment.

Bonding and brazing in a normal glow discharge are performed under a gas pressure of 1.33 – 13.3 kPa and at inter-electrode distance of $(5 - 15)\cdot10^{-3}$ m. Under such a pressure the gas temperature in a positive column of the discharge amounts to 1500 – 3500 K [8, 9], and size of the zone of the cathode potential drop which separates the positive column from the cathode (workpiece) decreases to fractions of a millimeter [10]. Under such conditions up to 80 % of the electric energy evolved in the discharge column is transferred by thermal conduction of gas to the cathode, which serves as an active heat sink, and, added to the impact of accelerated ions, provides its effective heating. Owing to the total effect on the cathode by two heat sources, the efficiency of heating amounts to 0.70 – 0.95 and depends to a considerable degree upon the gas pressure (Figure 1) [11].

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The specific property of the glow discharge as a surface heat source, which provides a substantial increase in its practicability, is the possibility of varying over wide ranges the density of the thermal energy flux on the surface of the parts joined. Variation in gas pressure p in a work chamber leads to a variation in current density j in the heating zone in an approximate relationship of $j \sim p^2$ [10]. This allows the current density to be varied from $10^{-3} - 10^{-2}$ to $0.1 - 0.5$ A/cm^2 through varying the gas pressure over a comparatively small range [6], which corresponds to a variation in the concentration coefficient from 0.01 to 0.50 (Figure 2). This makes it possible to use the glow discharge to provide both uniform gradual heating of thin-walled parts [12] and local, rather intensive heating of large billets [13].

The glow discharge is an intermediate form of a gas discharge, and under certain conditions it may change into a more stable form, i.e. electric arc, which leads to an inadmissible overheating and melting of a workpiece surface. Formation of the arc discharge may be caused by emissive spots present on the surface of workpieces, which result from its contamination with scale or grease, or presence of cracks or gaps of critical sizes [6], which lead to a local increase in the current density at the cathode.

The quality preparation of parts for bonding, use of shielding gas atmospheres with a decreased oxygen content and upgrading of design of a joint allow a fundamental decrease in the probability of formation of the arc.

Under bonding or brazing conditions, the wire- or strip-type steel anode is made as a circuit with a shape corresponding to that of a section heated. In this case the current density in the discharge is extremely nonuniform, i.e. at the anode and in the anode region it is almost by an order of magnitude higher than at the cathode. Contaminants in the form of oxide films are deposited on the surface of the anode or its local regions during operation. These films are polymerized in the discharge of vacuum oil vapours, etc., which have low electrical conductivity. The effective anode surface through which the discharge current is short circuited is decreased, thus raising the current density in the near-anode plasma [14]. An increase in the current density at the anode up to a critical value of $1.5 - 2.0$ A/cm^2 and higher leads to a further spontaneous contraction of the plasma by an intrinsic magnetic field [7, 10] to form an arc discharge channel. This negative factor is removed by periodical cleaning or replacement of the anode.

Transformation of a high-current glow discharge into the arc one is accompanied by substantial impact current overloading of a power supply and parts being joined. Such an overloading is decreased by connecting to the discharge circuit the ripple filters or using special arc-extinguishing devices, which react to variations in the current or voltage in the discharge circuit and affect them so that they are reduced to the values corresponding to the field of existence of the glow discharge. Devices used for such a purpose can be subdivided into three groups: devices which maintain the discharge current at a constant level [7], devices which switch off the supply voltage for a short period of time [15] and devices which decrease the discharge current by a certain value [16]. The time of formation of the arc discharge is $10^{-6} - 10^{-4}$ s [17]. Allowing for heat inertia of the parts, response of the devices can range from 10^{-2} to 10^{-1} s.

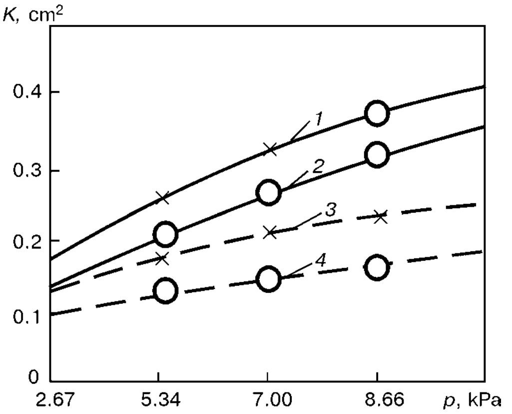

Figure 2. Dependence of the coefficient of concentration of the glow discharge upon the gas pressure in argon (*1, 2*) and helium (*3, 4*) at I = 2 (*2, 4*) and 5 (*1, 3*) A

Method which provides a more efficient increase in stability of the glow discharge is sectioning of electrodes [18, 19]. In the bonding and brazing processes a monolithic anode is replaced by a sectional one [20], the separate sections (segments) of which are connected to the positive pole of the power supply through decoupling ballast resistors of a rather high level — 100 – 500 Ohm (Figure 3). In this case, the arc formed in any cathode region or at any anode section will affect but slightly the burning conditions of the glow discharge at other sections. Besides, the current of the formed arc will be limited by a considerable external ballast resistance in this circuit. Thus, the effect of the arc on the parts joined is significantly decreased. However, this does not exclude the probability of their damage in the case of a long-time arc burning.

Limitation of the time of existence of the formed arc for a system of electrically decoupled electrodes is achieved by using a rotating electric field which runs about the anode sections at a certain velocity [21]. The arc formed at any of the anode sections at the next moment will be switched off from the electric circuit and extinguished. To prevent a repeated excitation of the arc at this section in its subsequent ignition, the velocity of rotation of the electric field is set so that all fluctuations caused by a short-time existence of the arc have enough time to disappear during a period of circulation of the electric current

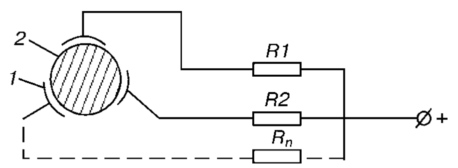

Figure 3. Schematic of heating using sectional anode: *1* — anode sections; *2* — cathode; *R*1, ..., *Rn* — ballast resistors

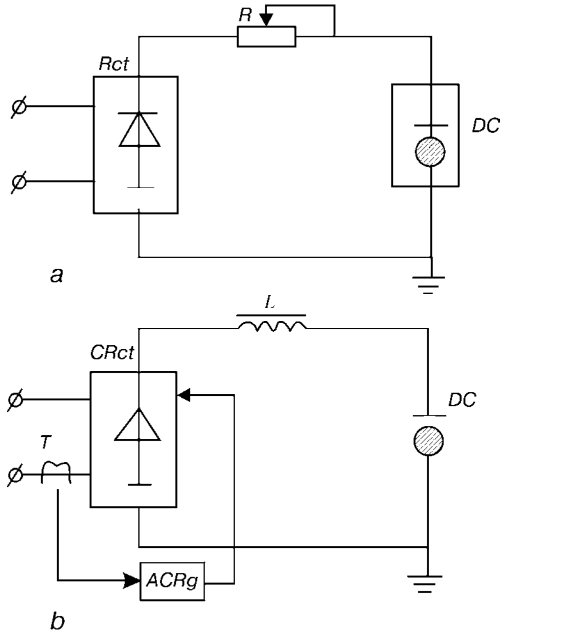

Figure 4. Diagrams of the glow-discharge power supplies with active ballast resistance (*a*) and those based on valve-type transducers (*b*): *Rct* — rectifier; *CRct* — controlled rectifier; *ACRg* — automatic current regulator; *DC* — discharge chamber; *R* — ballast resistance; *L* — ripple reactor; *T* — transformer

in the inter-electrode gap. Frequency of switching over of the anode sections should satisfy two contradictory requirements: it should be sufficiently high to limit the time of the arc burning at an individual section and, accordingly, decrease the degree of its impact on a workpiece, and, at the same time, it should be sufficiently low to eliminate conditions for its repeated excitation. The optimal frequency of switching over of the anode sections for discharge currents of 5 – 30 A is 500 – 2000 Hz, and decreases with an increase in the current. It is recommended to use high-frequency or pulse thyristors as elements which switch the anode circuits.

Power supplies with drooping or steeply drooping external characteristics are used to stabilize the burning conditions of the glow discharge. The simplest method for achieving such a characteristic is the use of a power supply with an active ballast resistance (Figure 4, *a*) [6]. The selected range of this resistance is from 1/3 to impedance of the discharge [22], which is 50 – 150 Ohm for the bonding conditions. Such a diagram is characterized by considerable losses of the electric power, i.e. the efficiency of a power supply is no more than 0.4 – 0.6. However, such power supplies are simple in manufacture and operation, are highly reliable and inexpensive and have a low mass (up to 5 kg per kilowatt). Therefore, they are widely applied in low-capacity commercial and laboratory installations. Substitution of a reactive ballast in the form of an inductance-capacitance converter [23] for the active one in the power supply made it possible to achieve an external characteristic close to a vertical one and, thus, widen the range of stability of the glow discharge. Power losses in such a ballast are markedly lower, and the efficiency of the power supply grows to 0.7 – 0.8. However, such power supplies have a substantial mass (from 11 to 22 kg per kilowatt, depending upon the design and capacity). They are much more sophisticated and expensive than those described above and have limited ranges of regulation of the parameters. Therefore, they failed to gain wide acceptance.

The increased-capacity installations (10 – 30 kW) use more effective controlled power supplies for the discharge. They are based on the valve-type converters (Figure 4, *b*) [24]. A steeply drooping characteristic of such power supplies is created by an automatic regulation of the current. They have a high capacity to mass ratio and their power losses are not in excess of 10 % of the total capacity of a power supply.

Technological capabilities of the glow discharge, combined with a relatively simple equipment, made it a promising heat source for the processes of pressure joining with preheating. At present it is applied for diffusion bonding of carbon and structural steels to hard alloys for the manufacture of cutting and forming tools [25, 26], joining technical glasses to metals [27], non-ferrous metals and alloys, except for aluminium, [28] in instrument making, iron-cobalt alloys to stainless steels for the manufacture of high-power ultrasonic transducers with concentrated or distributed parameters of the acoustic field [13], etc. The glow discharge has found application also for joining of metals by the soldering and brazing methods: from soldering of miniature resistor leads [29] and assemblies of electric-vacuum devices [30] to brazing of large-size units of steels and hard alloys [12, 31]. A specific feature of the glow discharge to penetrate into gaps, cracks and holes creates prospects for using it for cost-effective pressure bonding of complicated honeycomb and other types of structures characterized by a low heat inertia [7], owing to their uniform volumetric heating. The glow discharge is also applied for activation of the surfaces joined by ion bombardment. It is noted in [28] that preliminary treatment of copper with the glow discharge at a current of 0.32 A and gas pressure of 1.3 – 13.3 Pa provided an increased strength of the joints. Such a wide circle of problems solved by using the high-current glow discharge is attributable to its good adaptability to a variable range of parts, simple re-adjustment in changing types and shapes of the parts, high energy efficiency, low cost of the equipment owing to the absence of high-vacuum systems and tube generators, and the possibility of automation of the process. Available are commercial one- and multi-post installations for glow-discharge diffusion bonding with a capacity of 3 – 30 kW [24, 32] and brazing with a capacity of up to 60 kW [33], operating in the manual and semiautomatic modes. It is noted that the glow discharge holds promise for mass [30], custom and repair [25] production.

CONCLUSIONS

1. The high-current glow discharge is a promising and competitive energy source for the processes of solid-state joining of materials. Further investigations into

energy characteristics of the discharge, methods for increasing its stability, development of methods and conditions for ion cleaning and activation of the surfaces being joined are required for widening its technological capabilities.

2. The promising area is development of automated installations for glow-discharge bonding and brazing, and integrated technological processes involving pre- and post-joining operations.

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SOME PECULIARITIES OF PROCESS OF WELDING DIELECTRICS WITH METALS AND BETWEEN THEMSELVES IN ELECTROSTATIC FIELD

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ABSTRACT

The main stages of process of welded joint formation during welding in electrostatic field are described. Peculiarities of the process with respect to its implementation and selection of condition parameters of welding dielectrics with metals in a solid phase, as well as technical characteristics of the joints made by welding in an electrostatic field are considered.

Key words: *welding, electrostatic field, dielectrics, metals, electric discharge processes, welding conditions, process peculiarities, prospects*

Welding in an electrostatic field (WEF) of a high intensity can promote greatly the solution of problems of development of technological processes of producing permanent joints of dielectrics with metals and between themselves in radio electronics, aircraft and ship building, rocketry and also in aerospace engineering (Figure 1).

The WEF was studied over the decades in some countries of the world. The most important results were obtained in the USA. In CIS these works are carried out more actively in Russia and Ukraine, in the Chernigiv State University of Technology in particular.

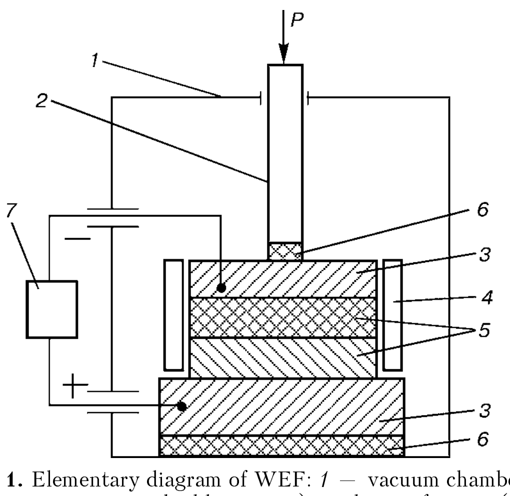

Figure 1. Elementary diagram of WEF: *1* — vacuum chamber (in welding in vacuum or shielding gases) or electric furnace (in air welding); *2* — rod for transfer of mechanical force (welding without external force of compression); *3* — electrodes; *4* — device for heating of parts welded (radiation heating); *5* — parts to be welded; *6* — isolators; *7* — high-voltage power source

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The research works carried out at the Chair of Welding Production of ChSUT made it possible to attain positive results in producing permanent, vacuum-tight joints of sitalls (for example, of SO-115M), inorganic glasses with metals and between themselves, to establish the regularities of the WEF process, to develop a number of technological processes and appropriate welding equipment for manufacture of components of gas discharge instruments [1]. Here, the combinations of materials, given in Table 1, were used for the development of real technological processes.

The WEF is based on the processes of polarization of a dielectric or a dielectric layer on the metal surface being welded (in welding metal with metal), which is heated to a preset temperature and placed to the high-intensity electrostatic field. These processes lead to the formation of a layer of the high-density electric charges on the surfaces being welded, ponderomotive interaction (PMI) between them, formation of a physical contact, chemical bonds and subsequent electrochemical interaction.

It was established that a main contribution to the development and formation of the physical contact is made by those kinds of the dielectric polarization which are set during a time of not more than $1\cdot10^{-7}$ s. This period is enough to have a physical contact and chemical bonds at not less than 97 % of nominal area of the contact. The further holding of the joint under the voltage promotes strengthening of the joint mainly due to migration polarization of the dielectric, whose duration determines the duration of the formation of the joint of a maximum strength. Over this period the processes of electrodiffusion, electrochemical reactions leading to the formation of a transition layer between the materials being welded, which is characterized by quite new properties and higher values of the strength characteristics, are realized [2].

The process of welding can be performed in any gas atmosphere: air, shielding gases, vacuum. In a general case the welding process is realized under normal atmospheric conditions. The need in some gas or mixture of gases, and also vacuum is defined by

Table 1. Combinations of materials being welded

Combination of materials being welded	*Interlayer*	*Thickness of interlayer, mm*	*TFLE·10^{-7}, K^{-1}*
SO-115M–Al	–	≤ 3*	SO-115M — 2(2.5 – 6.0) at 323 – 693 K
SiO_2–Al–SO-115M	Al	0.001	SiO_2 — (4.0 – 5.8) at 232 – 723 K
SO-115M–Al–SO-115M	Al	0.5 – 1.0	Al — 276.8 at 293 – 773 K
SO-115M–Al–Cu	Al	< 0.8	Cu — 170.0 at 293 – 393 K
SO-115M–Al–SO-115M	Al	0.001	

Notes: 1. Here SiO_2 is the quartz glass of KV type (GOST 15130–79); SO-115M (OST 3-104–77); Al — A999 (GOST 11069–74).
2. * is the thickness of aluminium component.

properties of the metal welded (an increased ability to interact with air oxygen and nitrogen, types of films forming at the surface being welded). For example, the welding of copper with inorganic glass and sitalls should be performed in vacuum to prevent the formation of a porous copper oxide film at the surface.

The investigations showed that the formation of the joint at WEF is hindered by electric discharge processes (EDP) proceeding at surfaces of the parts being welded and also in gaps between them [3].

The development of EDP in the welding plane is accompanied by the appearance of local volumes with an excessive pressure, causing the formation of air «bubbles» (lack of penetration) between the metal and dielectric, in the zone of which there are traces of discharges, i.e. burnouts. In an air gap («bubble») an ion layer of gas molecules is formed, which, being at the dielectric surface, compensates partially its surface charges, formed during the dielectric polarization, decreases the intensity of PMI and promotes the opening of microcracks at the surface of glasses and metals being welded.

The development of EDP in gaps near cathode leads to the appearance of surface currents and partial discharges in dielectric, thus shunting it. In addition, the quality of a polished surface of the dielectric welded, which is contacting the cathode (Figure 1, upper electrode), is greatly decreased because of the electroerosion. From this point of view the medium, in which the WEF occurs, should correspond to certain requirements of electrical strength (humidity of not more than 55 %, the absence of easily-ionizing particles in the zone of welding, etc.).

One of the obligatory conditions of producing quality welded joint in WEF is a preliminary treatment (mechanical and chemical) of the dielectric surface to be welded. Before welding this surface is polished to provide the preset roughness. Thus, for example, in welding of sitall SO-115M with aluminium the roughness of the sitall surface should not be more than $R_a = 0.02$ μm [4]. The roughness of the dielectric surface (in a general case the gap between the surfaces welded) at the moment of supply of the electrical voltage determines the mode of PMI and EDP.

The preliminary chemical treatment of the dielectric surface in organic solvents and inorganic solutions, except cleaning proper, makes it possible to ensure the preset properties both of the surface itself and also of the near-surface layer. Thus, investigation of 26 variants of single and 20 variants of combined treatment of sitall SO-115M before welding with aluminium showed that the maximum strengths of the joint are attained at a combined cleaning of sitall in the following sequence: acetone, inorganic solution with basic properties, chromium mixture. This is made not only due to an effective cleaning, but also to an activation of the process of establishing chemical coordination bonds between metal and dielectric by increasing acidity of the surface of the inorganic glass or sitall and also to an activation of the redox reaction between the surfaces being welded with a subsequent formation of complex compounds of oxides.

In addition, the treatment of inorganic glasses and sitalls in acid media at the final stage of cleaning weakens the EDP intensity in the gaps of the welding zone that is expressed in the decrease of quantity of burnouts and lack of penetration in the welding plane and also in the higher reproducibility of the experiment results.

The parameters of the WEF conditions include polarity, heating temperature (of welding) T_w, electrical voltage (intensity of electrostatic field between electrodes E_w), supplied to the object welded, rate of voltage supply, time of holding under voltage τ_w, level and mode of current (current density γ_w) passing through dielectric, rate of heating and cooling, external force of compression P. Ranges of main parameters of welding conditions for a number of combinations of materials welded are given in Table 2.

Criteria in selection of welding temperature is the preserving of design, technological and service properties of parts welded and also the assurance of completeness of proceeding processes responsible for the formation of the welded joint. Value T_w should be by 30 – 50 K higher than the temperature of beginning of the dielectric polarization and amount to (0.2 – 0.4) T_m in a general case, where T_m is the temperature of melting of the most fusible materials being welded.

The electrical voltage (intensity of electrostatic field between electrodes), supplied to joint being

Table 2. Ranges of main parameters of welding conditions

Combination of materials welded	T_w, K	$E_w \cdot 10^4$, $V \cdot m^{-1}$	$\gamma_w \cdot 10^{-3}$, $mA \cdot mm^{-2}$	τ_w, min	P, MPa
SO-115M–Al	623 – 723	18 – 20	2.0 – 3.0	5 – 10	10 – 25
SiO_2–Al–SO-115M	453 – 473	19 – 20	1.5 – 3.0	20 – 40	1 – 10
SO-115M–Al–SO-115M	623 – 723	18 – 20	2.0 – 3.0	5 – 10	10 – 25
SO-115M–Al–Cu*	623 – 723	18 – 20	2.0 – 3.0	5 – 10	10 – 25
SO-115M–Al–SO-115M	453 – 473	19 – 20	1.5 – 3.0	20 – 40	1 – 10

*Copper is oxygen-free.

welded depends mainly on the dielectric properties of dielectrics joined, their thickness and should ensure proceeding of processes responsible for the welded joint formation. In a general case, the higher E_w the lower temperature and time of welding.

The time of holding under the voltage (time of welding) is determined by those processes whose proceeding leads to the formation of a permanent joint. Moreover, the formation of the physical contact and establishing of chemical bonds is determined by the time of setting inertialess kinds of polarization (fraction of a second). The development of volume interaction with participation of electrodiffusion and electrochemical processes is determined by the time of realization of inertia kinds of polarization (migration in particular) and amounts from several to tens of minutes (depending on dielectric and chemical properties of the dielectric welded).

It was established that the voltage supply on the materials welded after reaching the welding temperature and increase in rate of its establishing reduces the effect of EDP, intensifies the intensity of polarization processes and promotes increase in the joint strength. In addition, the strength of welded joint depends on the intensity and ratio of rates in growth of polarization processes in dielectric and electric discharge processes in microgaps of the welding plane.

The level and nature of current (density of current) passing through the dielectric is determined by its dielectric properties, in particular by the dielectric permeability and welding temperature. For the development of PMI to provide the quality welded joint the dielectric permittivity should not be less than 6 and the current density at a selected temperature of welding should not be less than $1.0 \cdot 10^{-3}$ mA·mm^{-2}. The direct current is used for welding.

The current polarity greatly influence the joint quality. In welding metals with dielectrics the positive potential should be supplied to the metal. In a general case this is associated with an emission ability of the material surface in the welding plane being under the negative potential. The supply of the negative potential on the material of a high emission ability (for example, aluminium in case of welding with sitall) at presence of microgaps in the welding plane at the moment of voltage switching-on activates EDP and decreases the strength.

The level of external force of compression is not determining at WEF. The formation of the physical contact between materials welded occurs due to PMI. Under these conditions the external force of compression can be considered as a factor of intensification which can increase the joint strength to 40 % and provide vacuum-tight dielectric–aluminium joints at the latter thickness of up to 3 mm. The main requirement to the external force of compression consists of elimination of the gap between the materials welded before supply of electrical voltage for assembly. This intensifies drastically the process of separation of charges in dielectric and subsequent PMI. If the development of EDP in the welding plane can be prevented by other means (for example, by using interlayers of about 0.001 mm thick aluminium and rate of growth of polarization processes above the rate of EDP development in microgaps), the process can be performed without external compression loads or they will have a «fixing» nature (to prevent the pieces displacement in welding).

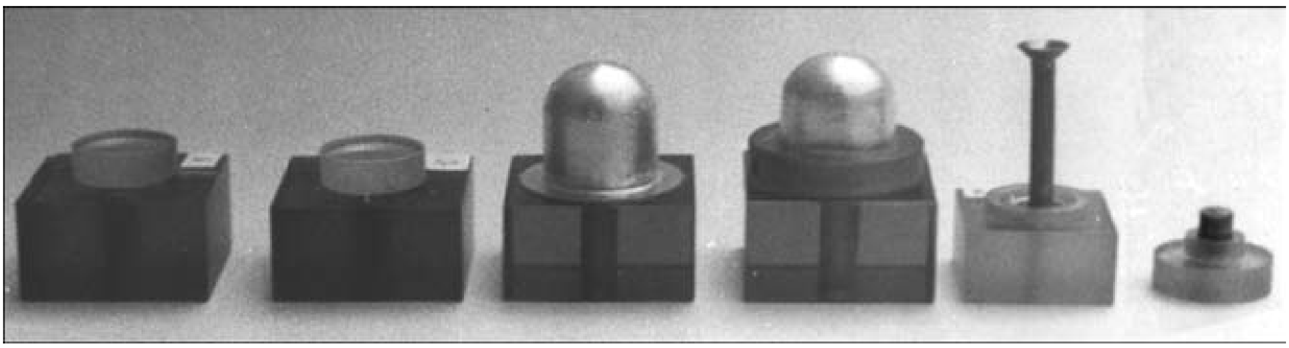

Figure 2. Components of gas discharge instruments, manufactured using WEF method

In addition, the relationship between the strength of welded joint (intensification of process of separation of charges in dielectric) and compression force and modulus of strengthening using aluminium interlayer was established.

The prospects of the WEF are based on the results obtained at its use for the manufacture of components of gas discharge instruments (Figure 2). As to the purpose and materials of components welded the WEF is comparable to the diffusion welding in vacuum, but it allows the process of welding of non-metals with metals to be improved to the higher technical and economical level, namely to provide:

• quality welded joints of dissimilar metal in solid phase at difference in temperature factor of linear expansion (TFLE) up to 46 times;

• low level of residual stresses in the zone of welding. Results of polarization-optical examination showed that residual stresses in the zone of welding are not more than 0.4 – 0.8 MPa (Figure 3);

• resistance to mechanical shocks and vibrations;

• resistance to thermal shocks at −60 – +120 °C (213 – 393 K);

• vacuum-tightness at leak detector sensitivity of not less than $1 \cdot 10^{-9}$;

• most strict requirements to precision;

• increase in yield of efficient products by 20 %;

• decrease in welding temperature by 200 – 250 K;

• increase in service temperature of components by not less than 150 K;

• increase in welded joints quality up to 50 %;

• reduction in cost of welding equipment down to 4 times.

Figure 3. Polarization-optical examination of components (level of residual stresses of 0.5 MPa in the zone of welding)

CONCLUSIONS

1. Welding in electrostatic field is a challenging method in producing vacuum-tight, precision components, made of materials with different physical-chemical properties, satisfying the most strict service requirements.

2. Practical use of the above-mentioned peculiarities of the process and recommendations for the selection of welding conditions makes it possible to define the optimum conditions for producing quality welded joint made by welding in electrostatic field.

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INTERNAL ELECTROSTATIC FIELDS AND THEIR ROLE IN SOLID-PHASE ELECTROCHEMICAL WELDING OF METALS

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ABSTRACT

Problems of formation of internal electrical fields in silicon–glass contact zone are considered. The effect of different factors on the formation of these fields is shown. The investigations of the transition zone of welded joints are presented.

Key words: *solid-phase electrochemical welding, materials welded, electrostatic field, transition zone, migration of ions*

Method of electrochemical welding can join ion-conducting glasses with semi-conductor materials, metals or metal alloys.* These glasses behave themselves at high temperatures in the same way as solid electrolytes in which the positive ions Na^+, forming at Na_2O dissociation, are mobile. Though the ohmic behavior of the glass as a solid electrolyte was studied comprehensively, a small attention was paid to the effects of polarization of regions adjacent to the anode. When applying a constant electrical voltage in the process of welding, a near-anode layer of glass is formed gradually in which the sodium depletion, and, as consequence, formation of electrostatic field of a high intensity are occurred. Electrostatic fields, formed in the near-anode region of the glass, cause some effects: they form internal compression forces which allow maximum contacting of materials surfaces being welded; create conditions of migration of oxygen ions to the surface of metal (semi-conductor), at which a transition binding oxide is formed; reduce the energy of the glass contact surface. As will be shown below, the width of depleted (polarized) zone is small and does not make it possible to study experimentally the distribution of potential in points of this region, to determine the width of this zone and electrostatic field inside this zone.

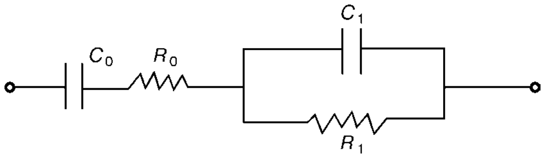

Figure 1. Equivalent electrical diagram of circuit of materials being welded

An assembly, including metal and glass elements and subjecting to a constant voltage (anode is metal), can be presented in the form of a simple equivalent electrical circuit (Figure 1) in which a near-anode zone of the glass is the purely capacitive reactance (C_0, R_0), and $R1$ and $C1$, connected in parallel, is the region of glass adjacent to the cathode. The transition processes and their quality can be interpreted easily by using the curves of current dependence on time (Figure 2). These curves can be recorded with the help of experimental installation, whose scheme is shown in Figure 3.

The quantitative parameter of the electrostatic field is its intensity which depends rather complexly on some parameters including welding voltage and its polarity, roughness of contact surfaces, air gap, sodium content in glass, dielectric properties of glass, temperature and time of welding, width of polarized region of the glass.

When the electrical voltage is applied to the assembling unit, heated to the welding temperature,

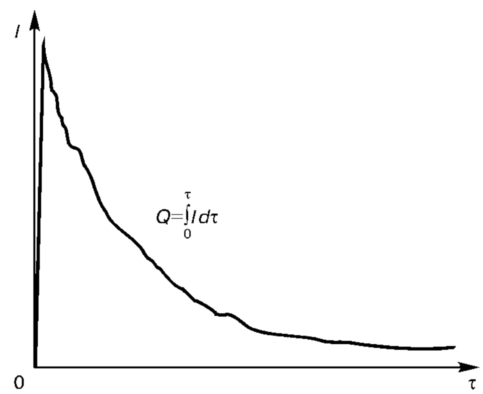

Figure 2. Relationship between current and time

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the contact surfaces are brought together as a result of an electrostatic force, decrease in air gap to zero, increase in width of the glass polarizing zone, formation and growth of oxide binding film between the glass and metal.

The outlined processes are associated with value of electricity transferred by ion current during welding process and it can be expressed by the following formulae:

width of polarized zone

$$h^i_{3c} = \frac{Q_i}{qNS}, \quad (1)$$

where Q_i is the value of electricity; q is the ion charge; N is the value of ions per volume unit; S is the contact area;

intensity of electrostatic field

$$E^i_{3c} = \frac{U}{h^i_{3c}}, \quad (2)$$

where U is the welding voltage;

strength of electrostatic field

$$F^i_n = 0.5E_{3c}E_0(E^i_{3c})^2; \quad (3)$$

thickness of oxide film

$$h^i_n = \frac{QM}{4S\rho F_{\rm F}}, \quad (4)$$

where M is the molecular mass of oxide; ρ is the silicon oxide density; $F_{\rm F}$ is the Faraday's number.

The only parameter which can be easily determined experimentally, is the value of electricity which is determined by area confined by ion current–time curve (see Figure 2).

It is naturally, that the intensity and ion current are the function of time and expressed by the following formula in the improved systems of units:

$$\frac{\partial E(h, \tau)}{\partial \tau} = \frac{1}{EE_0}[I - j(h, \tau)], \quad (5)$$

where $E(h, \tau)$ is the intensity of field in oxide or polarized region of glass at the distance h from metal at the moment of time τ; I is the density of initial current; $j(h, \tau)$ is the current density for given values h and τ.

These equations can be considered as consequence of the Gaussian theorem. As is seen, the important parameter is the dielectric permeability of the glass which can change by temperature, amount of sodium oxide. According to the analysis of two glasses «Pirex» and C 48-3 it is equal to 7. The change in E within ±30 % caused deviation in percentage of width of polarized zone of the glass and electrostatic field.

All the above-mentioned parameters can be determined by calculations on the basis of indirect investigations, such as integral method.

According to (1) the calculations of the width of the polarized zone of glass «Pirex» in contact

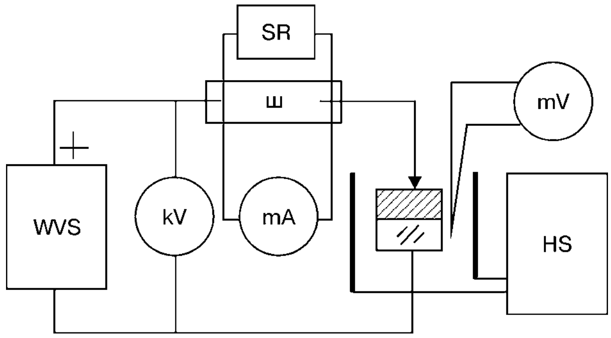

Figure 3. Diagram of electrical circuit of welding equipment: SR — self-recorder; HS — heat source; WVS — welding voltage source

with silicon (T = 400 °C, U = 1000 V, τ = 30 s) showed that it is $(210 - 2364)\cdot 10^{-3}$ μm. Electrostatic field is $(4.7 - 0.4)\cdot 10^6$ V/mm. The force of internal compression of samples is 628 – 495 MPa.

The formation of binding oxide films can be considered coming from the concept about ion conductivity of oxide at high intensity of field, complicated by the processes occurring at the interface of metal–oxide and oxide–glass.

The calculation showed that the thickness of oxide film forming during 30 s of welding is increased from 2 to $23\cdot 10^{-6}$ mm.

The effect of electrostatic field on mobility of positive and negative ions which can also have a positive or negative effect on the formation of the binding product (oxide) presents interest. The hypothesis about the role of oxygen ions of glass was confirmed by two experiments in which covar was used as an anode and glass «Pirex» as a cathode. The heating of this assembly in neutral medium to T = 400 °C did not reveal the formation of iron oxide film. The welding of the mentioned pair in the same medium with applying of welding voltage showed that the covar

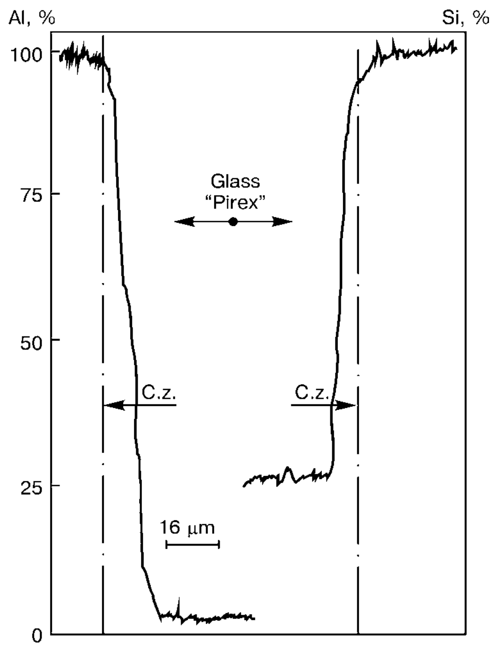

Figure 4. Distribution of aluminium and silicon in the zone of joining with glass «Pirex»

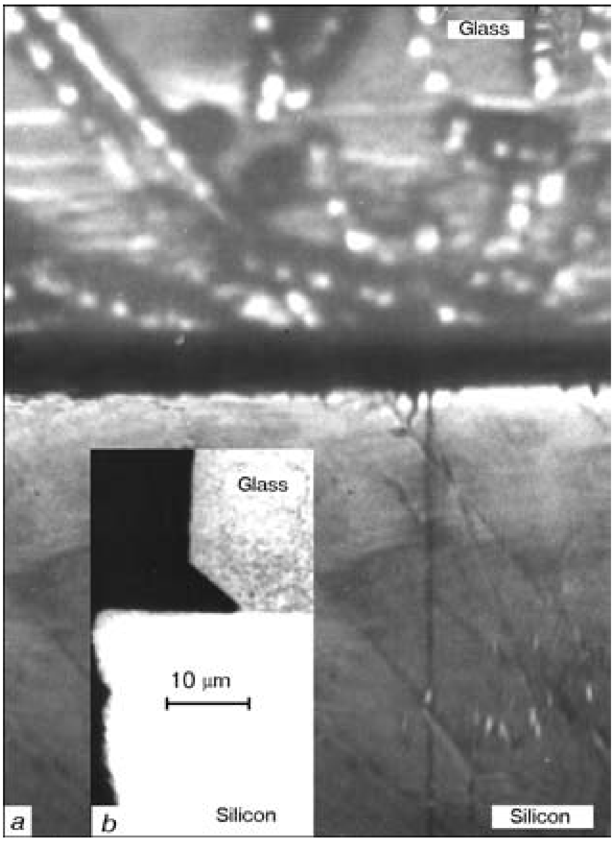

Figure 5. Transition zone of glass «Pirex»–silicon joint (×200) (increased by 10): *a* — top view; *b* — edge view

became grey in the contact zone, while the rest surface of the covar sample had an initial glittering colour.

Hypothesis about neutralizing of the electrostatic charge in the near-anode zone of the glass was also confirmed by experiments in which silicon, aluminium and silver were used as an anode. The X-ray microanalysis of the transition zone of the sample included silicon, aluminium and glass «Pirex» showed that ions of aluminium and silicon are diffused to the glass for a small depth and clustered at the anode (Figure 4). These pairs are characterized by a drastic decrease in ion current in time. At the same time this decrease is not observed for silver anode. This is due to the mobility of ions of silicon and aluminium which is somewhat lower than that of the sodium ions. Diffusion of oxygen and metal ions can neutralize charge partially or completely in the near-anode polarized zone of the glass.

Independently of mechanisms of migration of ions under the action of the electrostatic field it is evident that this process causes a remarkable change in the transition (boundary) zone of the glass with metal. These changes were observed in etching of section of the glass-silicon sample (Figure 5).

Thus, the values of the electrostatic field in the contact zone of glass with metal and internal forces of compression, and also the role of the electrostatic field in the processes of migration of positive and negative ions were established by using calculation-experimental methods. It is shown that the oxygen ions of the glass take part in the formation of binding transition zone between the materials being welded.

MODELLING AND SIMULATION OF TECHNOLOGIES AND EQUIPMENT DURING EDUCATION PROCESS OF WELDING ENGINEERS

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ABSTRACT

Problems of modelling and simulation of equipment and technology of fabrication of welded structures in the course of the education process are considered. Some laboratory works on subject «Fabrication of welded structures» are presented and described.

Key words: *education process, training of welding engineers, subject «Fabrication of welded structures», modelling, simulation, technological equipment, technological fixture*

The improvement in education and training of specialists is associated with mastering of active methods of training, among which the subject games, simulating real industrial conditions, occupy the leading place. For this purpose, it is possible to use the information posters, different mock-ups and models of a special equipment. The implementation of subject games in the course of the education process allows students to master some industrial habits.

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Modelling and simulation (prototyping) are important in the education process, in particular when the difficulties are encountered with an industrial practice and also with excursions for studying the real operating equipment.

One of the main subjects in education of the welding engineers is the fabrication of welded structures (FWS). At the Chair of Welding Production a complex of laboratory subject games has been developed, which allow students to study the technology of FWS using the scaled non-operating mock-ups and operating models, thus demonstrating the functioning of the objects studied. Basically, these are the technological processes and equipment which are most often used.

The results of modelling make it possible to receive certain conclusions about the operation capabilities of the technological equipment, required auxiliary fixture, optimum different variants in the technology of fabrication, etc. The modelling promotes prediction and taking of optimized solutions, as well as development of the optimum plans.

During development of each laboratory work the following problems were solved: selection of materials and structures, which provide a good modelling of the fabrication process; determination of type and scale of equipment (1:20 as usual) for preparation, assembly and welding; designing, manufacture, setting-up of models of the technological process; implementation of the subject game in the education process; working out of methodological recommendations.

The complex of laboratory works can be divided conditionally into three groups.

Group I. Mock-ups. In these works the mock-ups resemble originals only with a some degree of an appearance similarity, but having all the typical characteristics of the equipment, thus allowing students to remember the appearance. To organize the technological subject game for the selection of optimum engineering solutions the mock-ups have electrical connections and are equipped with a light and sound signalling.

Work 1. Optimum combination of welding equipment with welding fixture. Mock-ups of the fixture (different benches, tilters, rotators and manipulators) are fixed on the table and connected to the electrical mains. The mock-ups of the installations (mounted on the column, bicycle-type and L-shaped carriages, gantry, rolling beam) are freely displaced and electrically connected with plugs-and-sockets. The selection of the optimum combination is controlled by a signalling lamp and sound signal (Figure 1).

Work 2. Selection of optimum technology of fabrication of beams and shell elements. Mock-ups of the preparatory (straightening and bending rollers, gantry for gas cutting, guillotine, shot-blasting equipment, etc.), assembly-welding (benches for assembly of panels, circumferential welds) and welding (benches for welding panels from two sides, welding of longitudinal and circumferential welds, etc.) equipment are the objects which can be mounted on the table only in one position. Students arrange mock-ups in a definite sequence for two variants of fabrication of beams or shells. The correct arrangement of the mock-ups is controlled by a hermetically-sealed reed transducer on boards and table illuminated by a chain of lamps on the control panel.

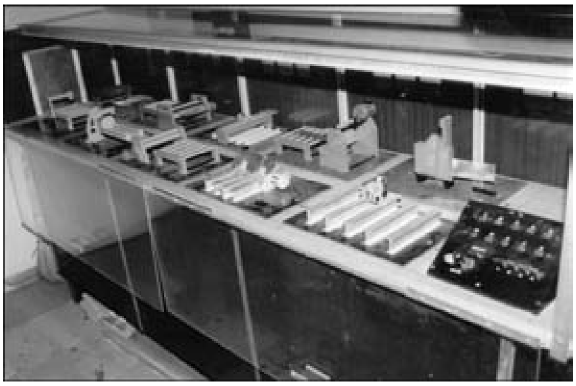

Figure 1. Mock-ups of mechanical and welding equipment for fabrication of I-beams (production line)

Group II. Demonstrating models. Operating models of equipment and mock-ups which reproduce the original in all its parts both outside and inside, are used for the transfer of information about its appearance and visual demonstration of the device and mode of the equipment operation.

Work 3. Load-carrying units. To evaluate forces and operation response, a set of mechanical (wedge, eccentric, rigging screw, spring and lever) and pneumatic (pneumatic cylinder and cell) clamps is used. All the clamps have paired supports which help to install units into the tongs of a rupture machine for using its force meter. In this work the capabilities of all the units are demonstrated visually.

Work 4. Versatile assembly devices (VAD). The set of VAD consists of thrusts, clamps and a support plate with T-shaped slots. This set makes it possible to create simplest devices for assembly and to assemble standard welded sub-assemblies (beam, girder connections, frame, reinforcement grid, pipe from U-tubes, pipe with a flange).

Work 5. Transporting devices. A model of a trestle for the shop of metal structures, furnished with an operating model of a gantry crane for handling of metal and ready welded structures is constructed. At the table wall a set of hoisting devices is located (slings, securing chains, traverses with different tongs, including those with electromagnets). A comparative analysis of operations of transporting of one piece made with their use is made by chronometry after study of the capability of different devices (Figure 2).

Work 6. Robotization of welding manufacturing. Its model consists of two parts (Figure 3):

• on the table, two manipulators for welding are located. The pipes are fixed in them. There are two welding robots, displacing along the axis of workpieces, for the manipulators service. In accordance with the programs, the robots and manipulators are operating simultaneously or in turn. Depending on

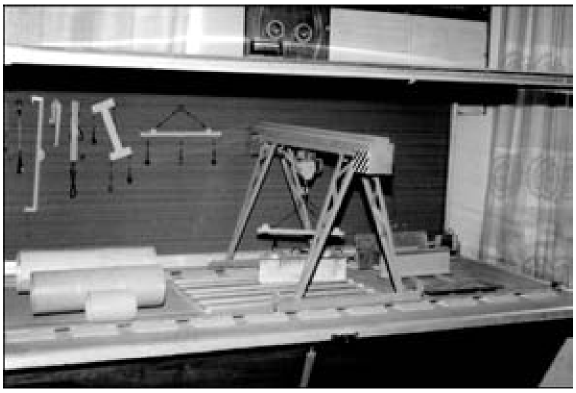

Figure 2. Mock-ups of transporting-rigging means and devices for displacement of sheets, I-beams and shells

Figure 3. Mock-ups of robotic complex for transporting and welding of shells

the movements, preset by programs, longitudinal, circumferential or spiral welds are made on the workpieces;

• on the table, a robotic complex is located, which assembles pipes from two U-tubes with a successive handling, laying and clamping according to the program. The work is finished by two welding robots which complete two longitudinal welds.

Group III. Reproduction of the equipment shape at a sufficiently close content of processes being simulated. The creation of the operating model of fabrication is the most hard-to-realize problem.

Work 7. Shop bay for fabrication of shell blocks and I-beams. To create the model of the operating fabrication is difficult, because it is necessary to provide a good visualization in training and to show the physical principle of processes of preparation and welding. The miniaturized manufacture of mock-ups of welded structures on operating models of the industrial equipment includes straightening rolls, guillotine, bending rolls, bench for welding of the shell longitudinal weld, bicycle-type carriage with a welding head, roller bench, two-support jig-tilter. All the equipment is connected to roller conveyors and arranged on three laboratory tables. During work the I-beams with four longitudinal welds and block of shells with two longitudinal and one circumferential welds can be produced, being sufficiently strong and very like by appearance to the real products.

Thus, the education and training games with the use of mock-ups and models enable students to receive the necessary knowledge and habits in the problems of equipment and technology of fabrication of welded structures and their optimizing.

INVESTIGATION OF THE TRANSITION ZONE IN BONDS BETWEEN HIGH-TEMPERATURE PIEZOELECTRIC CERAMICS AND METAL

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ABSTRACT

Interaction of materials in a bond between piezoelectric ceramics and copper, made through a chromium barrier interlayer, has been evaluated. The blocking effect of chromium on diffusion of bismuth into copper, as well as the value of diffusion of bismuth, which is not in excess of thickness of the chromium barrier interlayer, have been estimated.

Key words: *diffusion bonding of piezoelectric ceramics to copper, high-temperature vibration transducers, pressure, acceleration, chromium barrier interlayer*

Metal-piezoelectric ceramics pressure transducers and piezoaccelerometers, operating at a temperature of up to 600 °C [1], are used in measurement instruments to solve special problems related to monitoring of technological processes. The above devices are made from piezoelectric ceramics of the TV-2 grade [2], which consists mostly of oxides of titanium and bismuth. When joined to copper and during operation, components of piezoelectric ceramics (PEC) enter

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into chemical interaction with a structural material to form low-melting point copper–bismuth compounds within the contact zone, leading to fracture of the bond. Therefore, to eliminate this phenomenon it is necessary to use metal barrier interlayers (BIL).

The purpose of this study was to investigate a transition zone in the bond between bismuth-containing ceramics and copper, made through a chromium BIL.

Evaluation of interaction of ceramics with metal in solid-state joining shows that for the purposes of analysis the transition zone can be conditionally subdivided into three parts (Figure 1): zone of diffusion of ceramic components into metal, zone of reactive diffusion and zone of diffusion of metal components into ceramics. The zones adjoin each other and their thickness depends upon peculiarities of interaction of materials. Zone I, i.e. diffusion of ceramic components into metal, can be analysed by binary diagrams. Zone III can be analysed by variations in composition (structure) of ceramics. Zone II is a product of chemical interaction of oxides, which are part of ceramics, and metal.

Chromium was selected to be a material of BIL to block the effect of bismuth in the bond, which is attributable to its specific characteristics. Chromium is insoluble in bismuth, has a limited solubility when joined to copper and chemically stable oxides [3 – 5]. Thin layers of chromium can be easily deposited, from the technology point of view, on the surface of ceramics or metal by vacuum thermal evaporation. In addition, formation of chemically stable oxides in the transition zone of the bond leads to an extra enhancement of the blocking effect.

Diffusion bonding of bismuth titanate-based PEC TV-2 to copper was performed to make actual structures and metallographic sections. The bonding conditions were as follows: temperature 860 °C, compression load 1 MPa, bonding time 600 s, vacuum — not worse than $1.3 \cdot 10^{-3}$ Pa. Prior to bonding, the copper parts were etched in a solution of sulphuric acid (10 g/l) and potassium bichromate (50 g/l). Immediately before bonding the parts were wiped with alcohol.

Sections of the bonds were made in accordance with recommendations [5 – 7]. The bonds were ground at an angle of 90° to the surface of contact of the materials bonded and then polished using diamond pastes (ASM 7/10, ASM 3/2, ASM 1/0) in the PEC → Cu direction to avoid cold working and penetration of copper into pores in TV-2. The resulting sections were degreased with acetone and alcohol.

To reveal microstructure of the transition zone in the TV-2 + Cr bond, the latter was etched using the 10 % H_2SO_4 solution.

The transition zone in the TV-2 + Cr bond was evaluated by metallography, phase contrast method, a change in microhardness of the transition zone and by scan patterns of the section surfaces obtained using a scanning electron microscope.

The character of distribution of elements in the bonding zone was studied by optical and scanning electron microscopy using the JSM-35CF microscope.

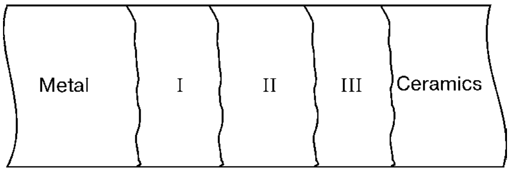

Figure 1. Schematic picture of the transition zone in the bond (see designations I – III in the text)

Examination of the transition zone by the phase contrast method (Figure 2) revealed several phases with different contrast. The largest changes in the transition zone of the PEC + Cr bond are characterized by a lighter field of the scan pattern of the PEC surface, as compared with the scan pattern of the initial ceramics. This is associated with an increase in the mean atomic number of PEC due to an increased concentration of bismuth, which is a result of its removal from the zone of reactive diffusion, because bismuth is forced out from its oxide by chromium. The transition zone of the bond is distributed non-uniformly to the surface of an angle lap section, which is likely to be caused by a non-uniform distribution of density in the bulk of PEC (porosity). A darker field of the scan pattern, as compared with PEC, is caused by a decrease in the atomic number of the phase (less than a mean value of PEC), which is a result of diffusion of chromium into PEC. The total length of the transition zone in PEC + Cr is not more than 6 μm.

The transition zone in the Cr + Cu bond cannot be evaluated by scan patterns of metallographic sections. No changes in contrast are seen in the scan pattern of the Cr + Cu transition zone. This is likely to be associated with close atomic numbers of chromium and copper or an insignificant concentration of chromium in the Cr + Cu transition zone, which does not allow the use of the phase contrast method.

Figure 3, made in reflected and secondary electrons, clearly shows the chromium BIL and transition zone of the TV-2 + Cr bond (while field). The zone of etching out of PEC amounts to 5 μm in size.

Evaluation of the transition zone by variations in microhardness of the TV-2 + Cr + Cu bond was made by the procedure described in [3, 7].

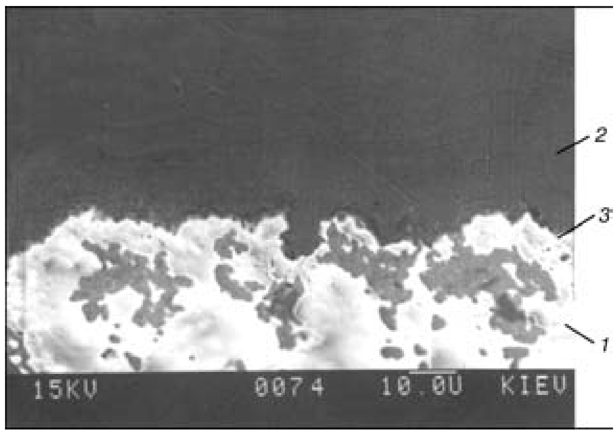

Figure 2. Microstructure of the TV-2 + Cr + Cu bond (angle lap section at an angle of about 9°, ×540): *1* — piezoelectric ceramics; *2* — copper; *3* — chromium (etchant — 10 % H_2SO_4 solution)

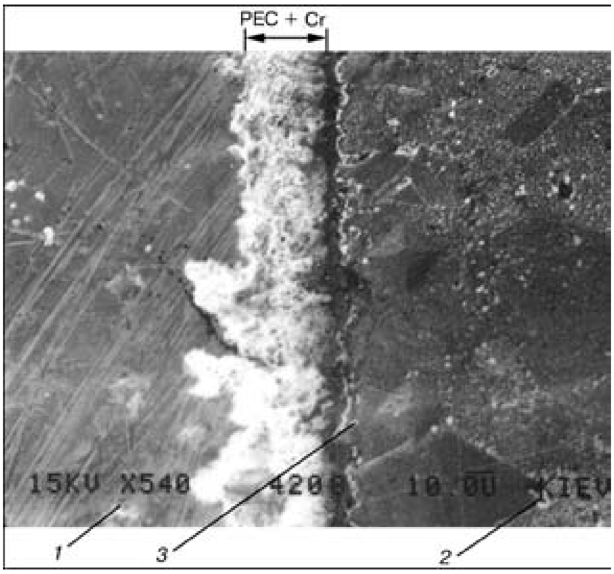

Figure 3. Scan pattern of a section in secondary and reflected electrons (angle lap section at an angle of 9°, ×1000): *1* — piezoelectric ceramics; *2* — copper; *3* — transition zone

Investigations showed that variations in microhardness took place only in the vicinity of the surface of contact of the materials joined (Figure 4). In the darkening zone of PEC up to 0.1 mm in size no changes in microhardness, as compared with a mean value, were detected. A decrease in microhardness near the transition zone of the PEC + metal bond is likely to be associated with a change in composition of PEC caused by diffusion processes taking place in the bond. A change in microhardness of PEC is fixed at a distance of less than 5 μm from the PEC–Cr contact surface. Changes in microhardness of copper are smaller and do not exceed 1.5 μm (Figure 4).

X-ray microanalysis of the character of distribution of elements was carried out using the «Link-860» and «Optec» X-ray energy dispersion spectrometer (EDS) by a method described in [8].

X-ray microanalysis of elements in the transition zone of the bond was made using EDS by points. Near BIL, a spacing of the microanalysis points was 2 – 3 and 5 μm at a distance of more than 10 μm from BIL.

The derived relationships of the intensities of radiation of elements (Figure 5) in the zone of contact of the

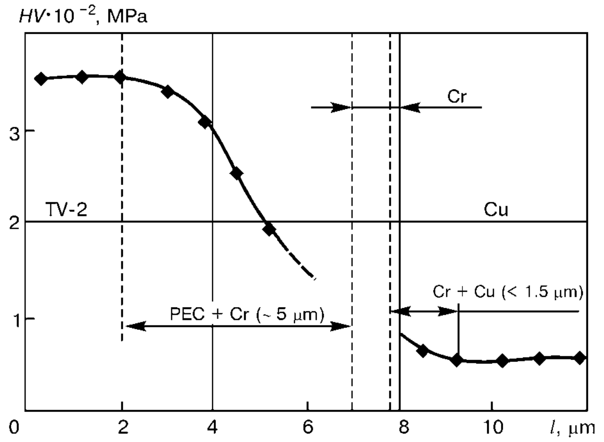

Figure 4. Variations in microhardness of the transition zone of the TV-2 + Cr + Cu bond (angle lap section at an angle of about 9°)

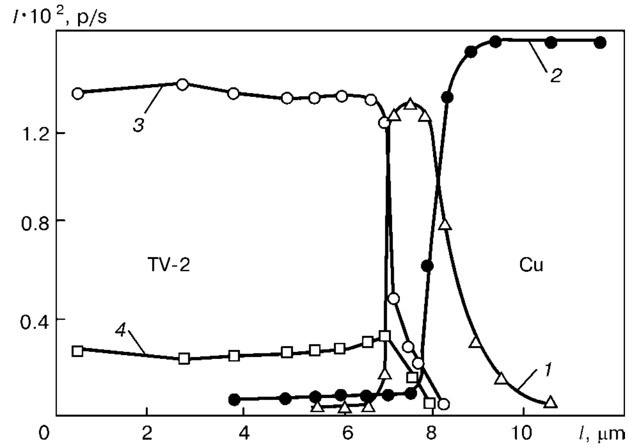

Figure 5. Dependence of the intensity of radiation of elements in the transition zone of the TV-2 + Cr + Cu bond (measurements made by points): *1* — CrK_α; *2* — CuK_α; *3* — BiK_α; *4* — TiK_α (angle lap section at an angle of about 9°)

materials show that chromium diffuses both into PEC and into copper in bonding performed under ultimate conditions for PEC TV-2. Penetration of chromium into PEC is not more than 1.5 μm, and that into copper — 2.0 μm. Copper diffuses into PEC through the chromium interlayer deep to 5 μm. Diffusion of the components of PEC TV-2, i.e. bismuth and titanium, is considerably limited by the chromium BIL. Penetration of bismuth into the bond is not in excess of thickness of the chromium BIL, i.e. less than 0.5 μm.

The character of distribution of elements in the transition zone of the TV-2 + Cr + Cu bond was determined by recording an image in characteristic radiation of CrK_α and BiK_α. Analysis of the scan patterns of an angle lap section showed than the chromium BIL (Figure 6, *a*) blocked mutual penetration of bismuth and copper. It is clearly seen from the scan patterns that distribution of bismuth elements (Figure 6, *c*) does not intersect distribution of chromium elements (Figure 6, *b*). The latter is characterized by a substantial non-uniformity, which is likely to be associated with non-uniform penetration of chromium into PEC.

Measurements of the character of distribution of elements show that the transition zone of the bond is asymmetrical. The zones of diffusion into copper are less than 3 μm and those into PEC from the chromium BIL are less than 6 μm. The chromium BIL causes a substantial limitation of mutual diffusion of the PEC and copper components. Penetration of bismuth into the bond is not in excess of thickness of the chromium BIL. This provides the blocking effect and prevents formation of a low-melting point eutectic of bismuth and copper.

Variations in structure of PEC in the transition zone of the bond were evaluated by the results of fractography analysis of the bond fracture surface. The metal–PEC bond fractured in PEC. Analysis was performed on samples with the fracture surface oriented at an angle of 8 – 15° to the plane of contact of the materials bonded. This allows the size of the analysed PEC + Cr transition zone to be increased

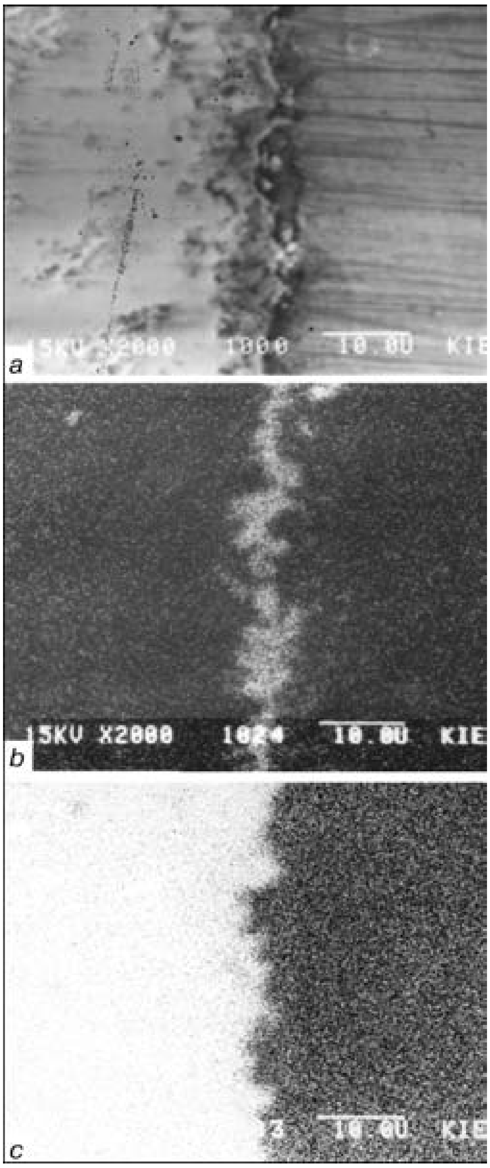

Figure 6. Scan patterns of the angle lap section of the TV-2 + Cr + + Cu bond in characteristic radiation: *a* — in secondary and reflected electrons; *b* — same in CrK_α radiation; *c* — same in BiK_α radiation

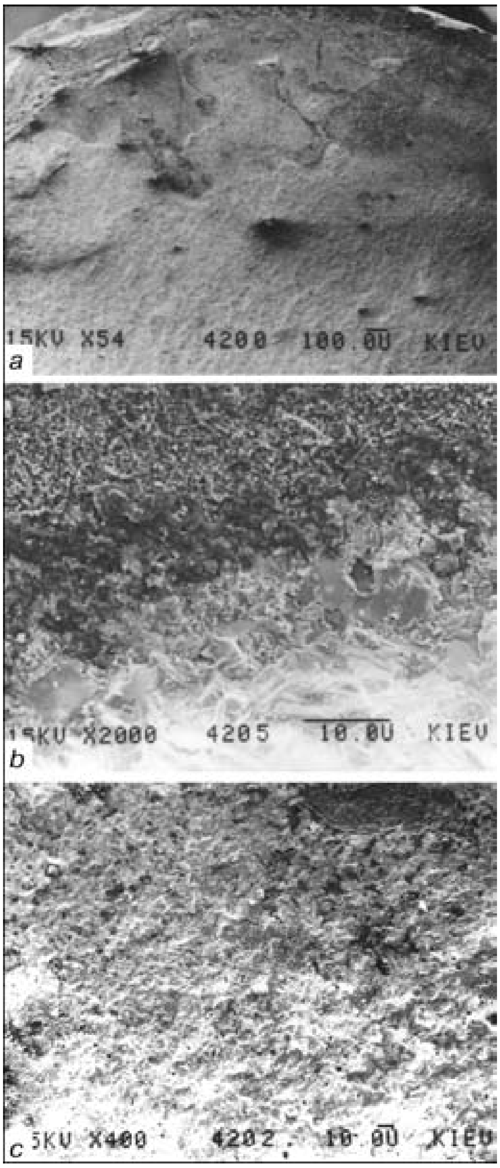

Figure 7. Fractogram of fracture surface of the TV-2 + Cr + Cu bond (in secondary and reflected electrons): *a* — bond; *b* — PEC + + Cr transition zone, ×2000; *c* — PEC + Cu transition zone, ×400

5 – 10 times. To produce a scan pattern with a higher contrast, nickel was sprayed on the PEC surface at an angle of 35 – 40° to the fracture surface. This nickel film was deposited to eliminate formation of a static discharge on the surfaces of ceramics being analysed and ensure the required contrast of the picture.

Figure 7, *a* shows the fracture structure, including the transition zone of the TV-2 + Cr bond. A phase which differs in the fracture structure from PEC TV-2 is clearly seen on the fracture surface. To identify composition of the phase, it was subjected to X-ray microanalysis. Measurements were conducted at the fracture points characteristic of PEC, phase with a changed structure and transition layer. Comparison of the measurement results on the intensity of radiation of elements of the phase with a changed structure showed that it additionally contained the chromium and copper elements (Figure 7, *b*). Evaluation of the size of the phases with a changed structure, conducted using a fractogram, showed that changes in the fracture surface of PEC did not exceed 15 μm. Allowing for an inclination of the fracture surface to the welding plane, this corresponds to the size of the transition zone of the PEC + Cr bond equal to 3 – 4 μm.

Blocking properties of BIL were evaluated. Bismuth diffuses through the chromium BIL during the process of diffusion bonding or heat treatment in operation. Interaction of bismuth and copper results in formation of a low-melting point eutectic with a melting temperature of T_m = 271 °C (T_m of bismuth is 270 °C). In cooling, differences in thermal expansion coefficients of PEC and copper induce thermal stresses, having maximum values in the zone of contact of the materials [3]. Upon formation of the eutectic of copper and bismuth between the chromium interlayer and copper, the bond fractures, which is caused by the presence of a liquid phase in contact between the materials joined. Therefore, the maximum time of operation of the TV-2 + Cr + Cu bond is limited to the time of formation of copper and bismuth eutectic.

The chromium interlayer is diluted in the materials joined during the diffusion mass transfer process. In this case its effective thickness increases. Thickness of BIL grows due to formation of transition layers of Cr + Cu and Cr + PEC, which are also characterized by an increased resistance to the bismuth diffusion. On the side of PEC from BIL — this is a multicomponent spinel based on the PEC components and chemically stable chromium oxide. On the side of copper from BIL — this is the zone of diffusion alloying of copper with chromium. Evaluation of distribution of the BIL elements in the bond by the scan pattern of a section in the characteristic radiation (see Figure 6, *b*) shows than it increased 1.5 – 2.0 times. Initial, before bonding, thickness of the chromium BIL is equal to 0.4 – 0.5 μm. As it is seen from the scan pattern of the section, it is 0.8 – 1.1 μm.

The minimum time of blocking of formation of the low-melting point bismuth and copper eutectic by the chromium BIL includes: 1) time of diffusion of bismuth through the chromium interlayer and 2) time of waiting [9]. The time of diffusion of bismuth through chromium into copper can be estimated using dependence taken from [9]:

$$\tau_d = \frac{\delta_{ef}}{2D}, \qquad (1)$$

where δ_{ef} is the chromium BIL thickness (effective) and D is the coefficient of diffusion of bismuth through chromium.

The time of waiting, associated with formation of a new phase, cannot be estimated, as thickness of the new phase is unknown.

The coefficient of diffusion of bismuth through the chromium interlayer was estimated by the Matano–Boltzmann method. This was done using an experimental dependence of the intensity of radiation of elements in the transition zone of the bond upon the section size (see Figure 5). Calculations were conducted using formula from [9]:

$$D = -\frac{1}{r}\,\tau_b\,\frac{\partial x}{\partial c}\int_0^c x\,dc, \qquad (2)$$

where τ_b is the bonding time; dx/dc is the angle of inclination of a tangential line to the concentration curve; $\int_0^c dc$ is the area under the curve of distribution of elements.

The coefficient of diffusion of bismuth through the chromium interlayer at a temperature of T = = 877 °C is equal to $2.6\cdot10^{-16}$ m^2/s.

Calculations of the minimum time of blocking of formation of the low-melting point copper and bismuth eutectic by the chromium BIL were conducted without allowance for the waiting time in formation of a new phase in the bond. For the BIL 1 μm thick, the permissible time of blocking is equal to

$$\tau_{ma} = \frac{\delta}{2D} = \frac{(1\cdot10^{-6})^2}{2\cdot2.6\cdot10^{-16}} = 1.9\cdot10^3 \text{ (s)}, \qquad (3)$$

during which the chromium BIL will retain the blocking effect and prevent formation of the liquid phase (copper and bismuth eutectic) in the bond.

CONCLUSIONS

1. Evaluation of interaction of materials in the PEC + + Cr + Cu bond during diffusion bonding under conditions close to the ultimate ones for TV-2 showed that chromium, featuring mutual insolubility with bismuth, limited solubility with copper and high resistance to oxidation, provided a blocking effect of bismuth in the PEC + Cu bond.

2. Measurement of sizes of transition zones and evaluation of the character of distribution of elements in them and variations in the PEC structure of the TV-2 + Cr + Cu bonds through the chromium BIL 0.45 μm thick showed that sizes of the PEC + Cr and Cr + Cu transition zones were in a range of less than 2 and 6 μm, respectively. The phase with a larger grain up to 4 μm in size is formed in the PEC + Cr transition zone. The depth of penetration of bismuth into chromium is not in excess of the BIL thickness, which prevents formation of the low-melting point eutectic of copper and bismuth and provides blocking.

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IMPROVEMENT OF METHODS FOR INCREASING QUALITY OF VACUUM COATINGS

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ABSTRACT

Problems of development of different-purpose quality coatings on polymers, glasses and metals are considered. The ways of improvement of technological processes of coating deposition are shown.

Key words: *vacuum thermal spraying, quality of vacuum coatings, new technologies, equipment*

The processes of treatment of materials using high technologies were considered traditionally expensive and they were used mainly in defence, aerospace industries, nuclear power engineering and others. During recent years the demand for these technologies increased in manufacturing, but in this case the need appeared to take into account the technical and economical aspects of their use.

The practice showed that during solution of definite technological problems the mutually exclusive requirements are often met. For example, it is necessary to produce the coating, being either transparent optically and characterized by a minimum electrical impedance (for systems of screening from radio bugging) or high strength on a soft substrate (friction supports, different functional units), or toning of a large area (2 – 5 m^2) with a high degree of uniformity and so on.

The dominating factor of producing the quality coating is a high adhesion with a substrate. The solution of this problem belongs actually to the diffusion welding technology which envisages the producing of uniform joining of two materials (in our case depositing layer and substrate). This process can be considered as remedy of a defect in a solid body, and welding as a method of elimination of this defect. However, unlike the canonical case when the materials welded are characterized by an affinity (mutual solubility, small difference in linear expansion factor), substrate material is often differed from that of the coating by its physical-mechanical properties from the coating deposited (metal + polymer, metal + glass, semiconductor + metal) [1, 2].

There is a wide arsenal of means and technologies of coating deposition. Below, two examples are considered, demonstrating that the direct transfer of traditional technologies does not always make it possible to produce new products of the preset quality. In each definite case it is necessary to take into account the peculiarities of any method of the coating deposition. The problem consists in that the most authors are based on the Raoult's law in a classical theory of deposition of decorating, strengthening and functioning coatings [3]:

$$\frac{P_A - P}{P_A} = N_B\,(N_A + N_B) = n_B,$$

where P_A is the pressure of saturated vapours of component A; P is the pressure of vapours of component A with an impurity; N_A, N_B is the number of moles of components A, B; n_B is the molar share of impurity B.

The essence of this law consists of the fact that with increase in content of the alloying component B the pressure of vapours of the depositing main component A is reduced proportionally to the growth of the molar share of the component B.

The neglecting of main postulates of this law led, in particular, to the fact that the technology of evaporation of a final weight of aluminium from the tungsten evaporator for producing reflecting layer on mirrors was referred to the category of standard at the legislative level (TS 01.003986001–94). The latent defect of this technology occurred to be the deposition from intermetallics that is inevitable in evaporation of final weights because of the limited mutual solubility of aluminium in tungsten. In practice, only 15 – 20 % of the initially deposited material (for installation of UVN-15, UV-18 type) correspond to the requirements of GOST 17716–91 by reflecting properties, the rest percentage is the transition fractionating layer of the intermetallics. The life of this coating is rather low. The dull color and the separation of the reflecting layer was observed after 1.5 – 2.0 months of service.

To eliminate this defect a partial modification of the equipment and change in the technological process have been suggested. The upgrading of the equipment consists in installing of unique systems of ion purification and crucible evaporation (mounted almost on all the park of the vacuum equipment of CIS). The

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system of the ion purification is furnished with a differential flow regulator and enables treatment of surfaces for the coating deposition using anomalous ion discharge. The conditions of purification (U = 5000 – 7000 V, I = 0.5 – 1.5 A) are characterized by such effectiveness that even resistive method of evaporation makes it possible to reach the strength of the coating adhesion at the level of 250 – 270 MPa. The use of crucibles, made from the alumooxide ceramics, reduces the effect of the evaporator material on the coating being deposited almost to zero.

The second example of a non-rational use of technological capabilities of the equipment consists in producing strengthening coatings on the base of the titanium nitride on the metal cutting tool. According to the existing standard technological process «Ion plasma coatings for cutting tools» (OST 4.054.070–85), the cleaning of the surfaces to be deposited is performed by the method of a pulsed bombardment of the cathode with ions of a spraying material. The high efficiency of cleaning is accompanied by a negative phenomenon, such as a significant zonal heating of the component surface at a high pressure of residual gases in a vacuum chamber. This action and also the separate use of processes of cleaning and coating deposition lead to the formation of secondary oxides at the component surface, sources with a deep diffusion embedding of carbides, to the grain growth and appearance of the microcracks. The microhardness of the coating does not exceed 16000 MPa. The drastic change in the technology leads to a significant increase in the coating microhardness (up to 25000 MPa on average). This is due to the realization of the continuous process which combines cleaning and spraying. Giving a constant negative potential to the substrate it is possible to reach that moment when the high-energy particles, entering the substrate and embedding in it, can be neutralized and reflected as neutral or metastable particles. This makes it possible to provoke the secondary electron emission with a substrate material spraying.

It was established that when such method of cleaning is used the stabilization of the ion current at 3 kV accelerating voltage and 5 Pa nitrogen pressure in the chamber occurs even after 5 min. This gives a feasibility to shorten the process of treatment by 2 times at a considerable improvement of the coating quality. The device for a smooth control developed for the installation «Bulat-6» could provide rates of coating deposition on the 30 mm diameter component up to 12 – 17 μm/h.

Thus, it is not necessary to use in practice the «blind» transfer of technologies of vacuum deposition, used in producing pieces with functional coatings, on the products of the similar type.

It is not desirable to use the technological processes delivered together with a vacuum equipment, as basic processes, because the universality gives very often the poor quality.

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