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CONTENTS

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WELDING CONSUMABLES: STATE-OF-THE-ART AND TENDENCIES OF DEVELOPMENT

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Data are presented about today production and consumption of steel in different regions of the world. The progress in machine-building, shipbuilding, civil engineering and other branches will require the reduction in mass of welded structures, increase in their reliability and life, reduction in energy consumption in welding operations. The above-mentioned problems can be solved by using high-strength low-alloy (HSLA) steels in critical structures. Data are given about the state-of-the-art of metallurgy and technology of HSLA welding in Russia and Ukraine. The problems of welding HSLA steels and tendencies of their development are considered and trends for their further investigation are formulated. State-of-the-art of development of general-purpose welding consumables is described and recommendations for their improvement are given.

Key words: *arc welding, welding consumables, high-strength low-alloy steels*

The last XX century was a period of origin and progress of welding. During the elapsed time many new welding processes, from welding with a carbon and metal electrode to electron beam, laser, hybrid laser-arc welding, were created. Nevertheless, among the numerous methods of fusion welding, the arc welding is dominating until now. The range of materials being welded is very wide: low-carbon and alloy steels, alloys on the base of titanium, aluminium, molybdenum, tungsten, intermetallics and ceramic materials. Specialists throughout the world state with a full confidence that steel, as a structural material, will dominate at least in the first quarter of the XXI century.

The production of steel in the world is continuously growing and progressing (Figure 1), it was about 830 mln t in 2000 [1]. For the first seven months of 2002 more than 505 mln t of steel were produced in the world. From the data of International Institute of Steel, the consumption of this material will soon increase by 4.3 %. The steel production in Asia is growing most rapidly. 42 % of steel production (Figure 1) and 40.6 % of its consumption (Figure 2) are related to the share of countries of this region.

People's Republic of China occupies the leading place in steel production during recent six years. In 2001 it produced 151.6 mln t of steel (it is 18 % of world's market) [2]. Since 1996 the steel production in China increased by more than 50 %.

In 2000 the steel production in Russia was 58 mln t, in Ukraine — 31 mln t, i.e. it almost 2 times decreased as compared with 1990. Because of disintegration in the field of machine-building and construction, the steel consumption in these countries several times decresed that caused the reduction in production of welding consumables. In 2000 only 343000 t of welding consumables were produced in Russia, Ukraine and other CIS countries. Among them 80 % is amounted to the share of coated electrodes, solid wires for shielded-gas welding — 9.7 %, flux-cored wires — 1.6 %, fluxes — 8.7 % [3]. Output of materials for the mechanized welding was most drastically decreased. Many large specialized productions had to work at a continuous low capacity. The prices for raw materials and power suppliers were significantly increased. The old grades of consumables were produced, there were no appropriate marketing of products. Under these conditions many specialized productions fall into decay, numerous small companies are appeared which produce cheap and often non-quality welding consumables.

It seems that this phenomenon is temporary. Under the present conditions only large strictly-specialized

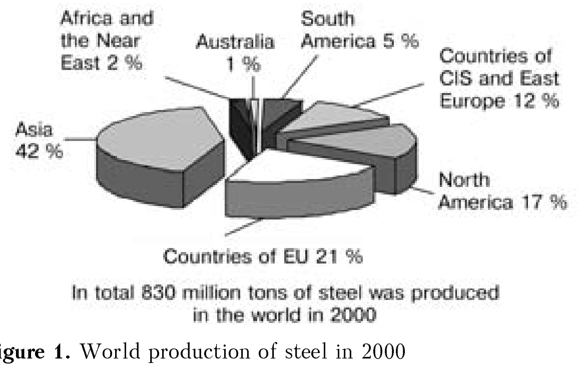

Figure 1. World production of steel in 2000

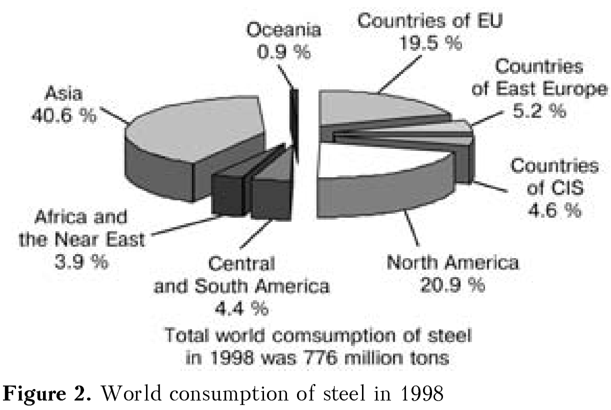

Figure 2. World consumption of steel in 1998

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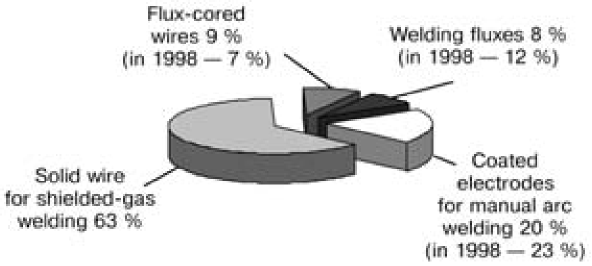

Figure 3. Share of output of welding consumables in EU countries in 2000

productions which should progress with a close coopaaration with research organizations are capable to offer the competitive products. When predicting the development of arc welding in our country we should, undoubtedly, be oriented on the industrialized countries.

Figures 3 and 4 give data about output of welding consumables of different types in EU countries and Japan [1, 4], Figure 5 [1] presents the results of evaluation of a metal share deposited by different methods of arc welding in EU countries, and Figure 6 illustrates data about the output of different-purpose coated electrodes for manual arc welding [5].

In the industrialized countries the volume of applicaion of the mechanized shielded-gas welding with solid and flux-cored wires is widened and a share of the manual arc welding is reduced. For example, in

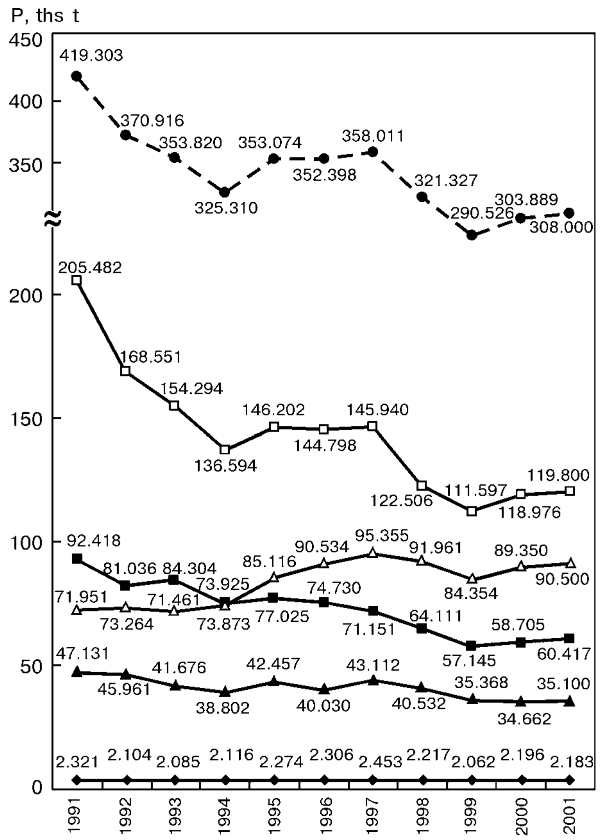

Figure 4. Production of welding consumables (P) in Japan during the period from 1991 to 2001: ❒ — solid wire for shielded-gas welding; Δ — flux-cored wire; ■ — coated electrodes; ▲ — materials (wire and flux) for submerged arc welding; ◆ — non-consumable electrodes and materials for other processes of welding; ● — in total

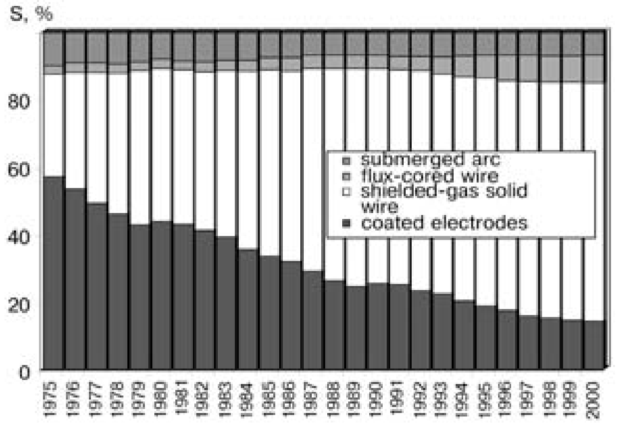

Figure 5. Share (S) of metal deposited by different methods of arc welding in EU countries during 1975–2000

countries with an advanced shipbuilding (Japan, Korea) the volume of flux-cored wire application is increased. In EU countries the welding in gas mixitures on argon and CO_2 base using a solid wire is dominated among the mechanized methods. A high share of application of coated electrodes is typical of the developing countries with a cheap manpower. A share of submerged arc welding in EU countries has been stabilized since the 1990s until now (Figure 5).

In Russia and Ukraine the situation in the field of application of welding consumables will be, undoubtedly, changed. The progress in the machine-building, shipbuilding, civil engineering, oil-chemical and oil-refining complex and other branches of industry, as well as payment of welder's labour and social problems will require new solutions.

At present the following requirements are specified to the welded structures: reduction in their mass and power consumption in manufacture, increase in reliability and service life. The progress in this direction is associated with the further widening of high-stength low-alloy (HSLA) steels application, which are an important development of the second half of the XX century. In 1994, the world production of HSLA steels reached about 80 mln t at an annual increase in production by 5 % and more [6]. Now a share of production of this material has been more increased.

Many years in the USSR the works were carried out for the development of HSLA steels and technologies for their welding. In TsNIIKM «Prometej» in collaboration with the E.O. Paton Electric Welding Institute the methods of production of high-strength

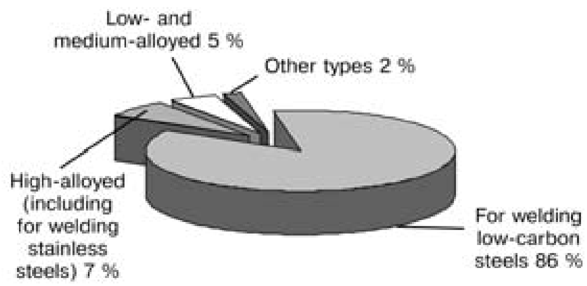

Figure 6. Share of production of different-purpose coated electrodes in EU countries in 2000 (rutile electrodes amount approximately to 2/3 of a total share of electrodes for welding low-carbon steels)

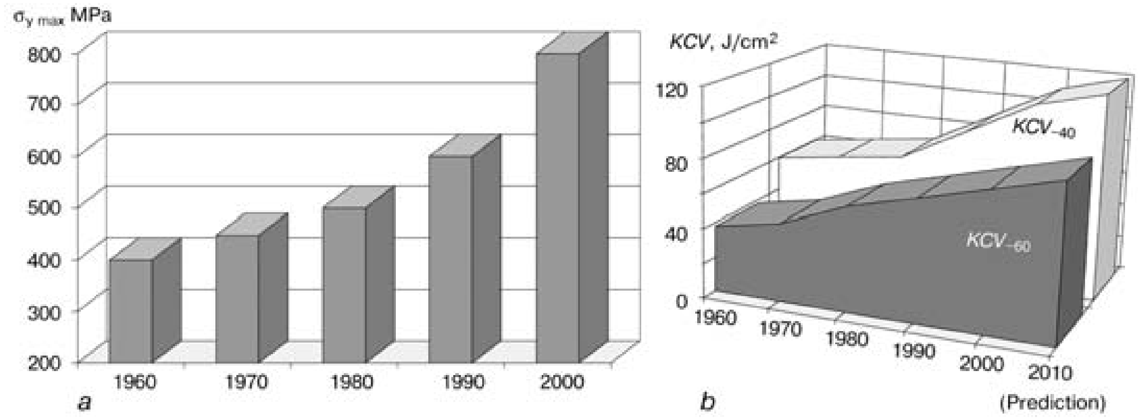

Figure 7. Mechanical properties of welded joints from HSLA steels: *a* — maximum yield strength $\sigma_{y\ max}$; *b* — impact toughness *KCV*

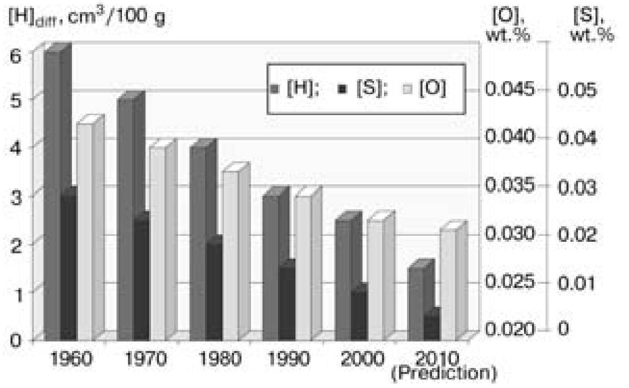

Figure 8. Content of impurities in welded joints from HSLA steels

hull steels of AB type with up to 1000 MPa yield strength were developed (characteristics of these steels are given in [7]). Content of carbon and alloying elements in them was decreased to the level providing a through hardening. After heat treatment the steel structure represents a highly-dispersed sorbite with a solid-solution hardening of a ferritic matrix whose presence ensures high strength, ductility and a good weldability. Figures 7 and 8 present data about the progress in metallurgy and technology of welding HSLA steels. Owing to the investigations carried out in Ukraine a significant decrease in concentration of hydrogen, sulphur and oxygen in weld metal, increase in its mechanical properties, improvement of weldability and also decrease in a preheating temperature were attained. Data about the content of impurities in modern HSLA steels are given in Table 1.

Main tendencies in the development of HSLA steels. When developing welding consumables and technologies of welding the following factors should be taken into account: decrease in the range of concentrations of alloying elements; increase in combinations of microalloying elements; reduction in carbon content; decrease in a mass fraction of residual elements, sulphur and phosphorus; decrease in concentration of hydrogen, nitrogen, oxygen; increase in homogeneity and level of mechanical properties; improvement of deformability; improvement of weldability and toughness of welds and joints.

The most important problem in HSLA steel welding is the prevention of a brittle fracture of welded joints. This phenomenon is caused by structural transformations in weld and HAZ, and also by embrittlement action of impurities, dissolved in metal, and, first of all, hydrogen, manifasting itself in initiation of hydrogen-induced cracks and delayed fracture of welded joints. To prevent this, the advanced technologies of welding steels of the above-mentioned type envisage the use of preliminary and auxiliary heating of products. These are energy- and labour-consuming and also expensive operations (Figures 9 and 10), whose fulfillment requires a high technological culture of production. However, they do not always provide the absence of cracks in the welded joints. Due to a high temperature of products, caused by preheating, the labour condiions of assemblers and welders are drastically deteriorated.

The manufacture of structures from HSLA steels without preheating is one of major problems of arc welding today. The results of investigations on the problem of hydrogen behaviour in welded joints are summarized in works [8–17]. This problem is actual for all the methods of arc consumable electrode welding and should be obligatory taken into account in the development of welding consumables.

The preheating temperature of structures depends on the concentration of a diffusive hydrogen in weld metal, carbon equivalent P_{cm} and linear energy of welding q (Figure 11).

In steels and welded joints the hydrogen transfer is determined by its diffusion in fields of a gradient of concentrations and stresses, thermodiffusion, sur-

Table 1. Content of impurities (wt.%) in HSLA steels

Class of steel	*S*	*P*	*N*	*O*	*H*	*N, O and H (in total)*
Conventional	≤ 0.005	≤ 0.010	0.006	0.004	0.0002	≤ 0.0250
Pure (economically rational)	≤ 0.002	≤ 0.005	0.004	0.001	0.0001	≤ 0.0120

σ_y, MPa	Temperature of parent metal, °C			
	10–40	41–70	71–100	101–130
315	–25	0	+10	+20
390	0	+10	+20	+60
500, 620	+10	+20	+80	+100
690	+80	+80	+100	+120
780	+80	+100	+120	+120

□ Without preheating
▨ Pre-drying (at 40–50 °C)
■ Preheating

Figure 9. Required temperature of parent metal preheating (concentration of diffusive hydrogen in deposited metal should not exceed 2 cm^3/100 g)

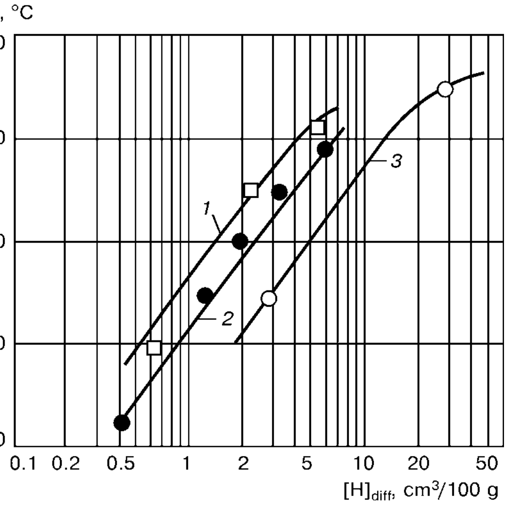

Figure 11. Dependence of critical temperature of preheating T_{cr}, required for prevention of crack formation in welding steel with 460 MPa yield strength [8] on concentration of diffusive hydrogen $[H]_{diff}$ in weld metal: *1* — submerged arc welding (q = 3.0 kJ/mm, P_{cm} = 0.235); *2* — welding with coated electrodes (q = 1.7 kJ/mm, P_{cm} = 0.235); *3* — welding with coated electrodes (q = 1.7 kJ/mm, P_{cm} = 0.212)

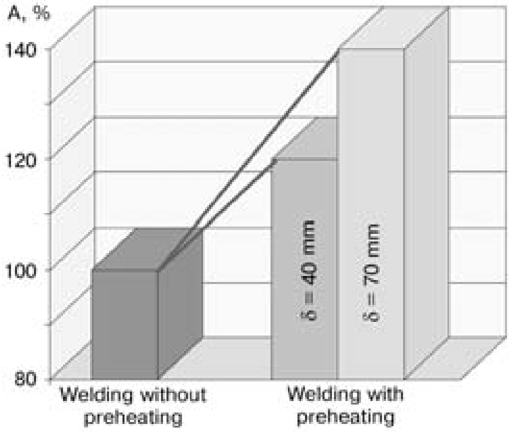

Figure 10. Cost (A) of welding jobs [7] (δ — thickness of steel being welded)

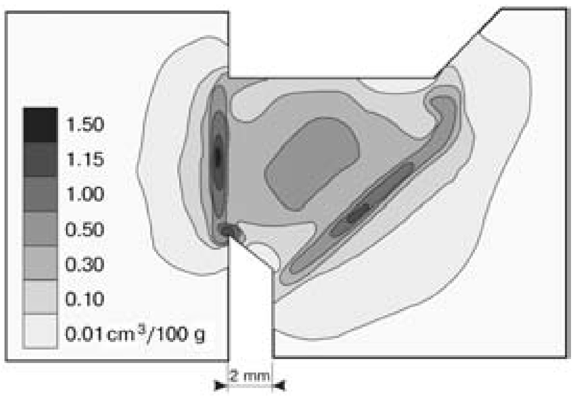

Figure 12. Distribution of hydrogen concentrations in metal of weld and HAZ 5 h after welding without preheating [8]

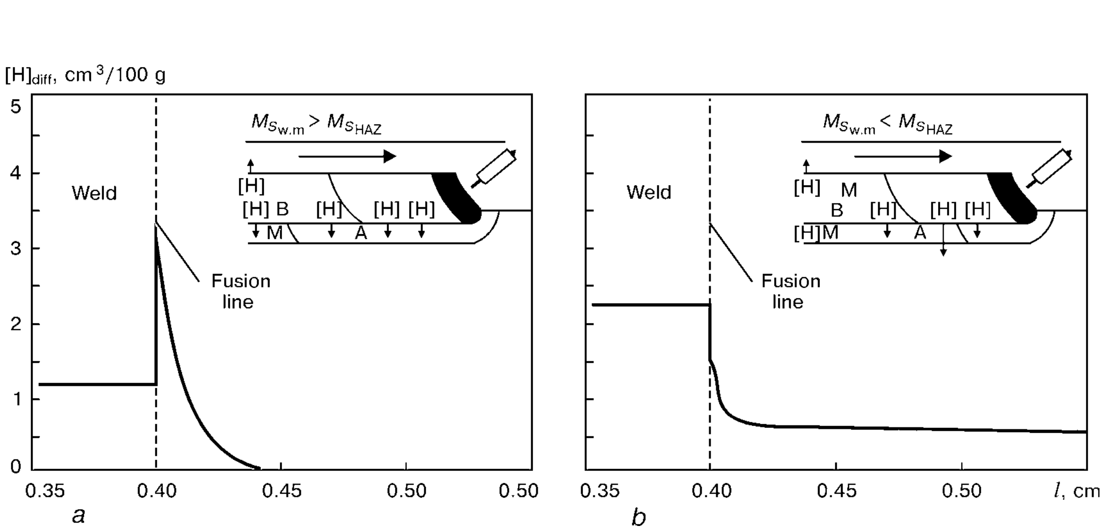

Figure 13. Distribution of hydrogen in fusion line in metal of welds and HAZ, different in chemical composition: a = $M_{S_{w.m}}$ at 600 °C, $M_{S_{HAZ}}$ at 500 °C; b — $M_{S_{w.m}}$ at 500 °C, $M_{S_{HAZ}}$ at 600 °C (l — distance from weld axis; A — austenite; B — bainite; M — martensite)

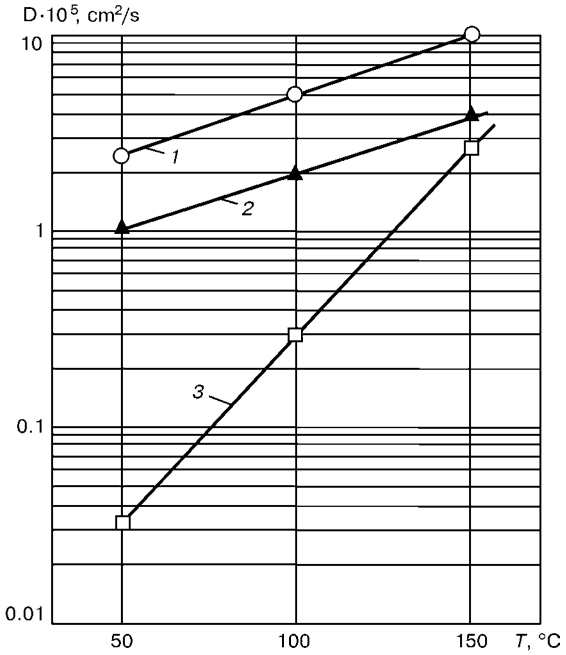

Figure 14. Temperature relatonships of coefficient of diffusion of hydrogen (D) in metal of welds produced using basic (*1*) and rutile (*2*) electrodes, and constants of rates of hydrogen evolution from «traps» in metal deposited with rutile electrodes (*3*)

face diffusion, diffusion in structure defects, transportation, dislocations. Modelling of hydrogen distribution in the welded joint in the presence of stresss raiser was made by N. Yurioka (Figure 12). As is seen from the Figure, hydrogen in the welded joint is distributed non-uniformly, the increased concentration is observed in HAZ and along the fusion line. Nature of its distribution depends on ratio of temperatures of the beginning of martensitic transformation in metal of welds $M_{S_{\rm w.m}}$ and HAZ ($M_{S_{\rm HAZ}}$) (Figure 13). At $M_{S_{\rm w.m}} > M_{S_{\rm HAZ}}$ the martensite in weld metal is formed earlier than in HAZ, which becomes a barrier for hydrogen transportation. A high concentration of diffusive hydrogen is observed in it and potential conditions are created for crack formation (Figure 13, *a*). At $M_{S_{\rm w.m}} < M_{S_{\rm HAZ}}$ the martensite in HAZ is formed earlier than in weld metal (Figure 13, *b*). In the latter the concentration of diffusive hydrogen is higher, therefore, the probability of crack formation is larger [10].

Hydrogen diffusion into weld metal depends on its chemical composition, structure and also the presence of defects in the form of pores and non-metallic inclusions. Data about the mass transfer of hydrogen into weld metal are given in Figure 14.

The rate of hydrogen mass transfer into metal of welds made by basic electrodes is several times higher than that in welds made using the rutile electrodes. This is due to the presence of a large amount of hydrogen «traps», i.e. non-metallic inclusions and small pores in metal of welds produced by the above-mentioned method. Hydrogen «traps» can be formed additionally in weld metal during its deformation. With increase in the amount of defects in metal the mass transfer is delayed [11].

The concentration of duffisive hydrogen in metal of welds can be decreased by its microalloying with rare-earth metals and hydride-forming elements. Figure 15 gives data about the effect of rare-earth metals and yttrium on diffusive hydrogen concentration. When the rare-earth metals are added the redistribution of hydrogen in weld metal is occurred: the concentration of duffusive hydrogen $[H]_{diff}$ is decreased and that of residual hydrogen $[H]_{res}$ is increased. Oxysulphides, formed in microallying of welds with rare-earth metals, accumulate hydrogen.

Redistribution of hydrogen in metal of welds can occur at phase transformations and depends on the cooling rate. Then, the residual austenite plays the role of «traps» in weld metal (Figure 16) [18].

The hydrogen trapping by «traps» is explained by a low rate of mass transfer of hydrogen in residual austenite. Using standard measurements, it was determined that in the presence of the residual austenite in weld metal the hydrogen concentration is underestimated at the temperature up to 250 °C. This should be taken into account in prediction of hydrogen-induced crack formation in the welded joints.

The hydrogen concentration in welded joint metal depends mainly on the amount of moisture and hydrogen-containing elements in electrode coatings, fluxes, flux-cored wire cores, etc. In development of ultralow-hydrogen welding consumables the hydrogen concentration in wires and parent metal should be accounted for. To decrease it in raw and ready

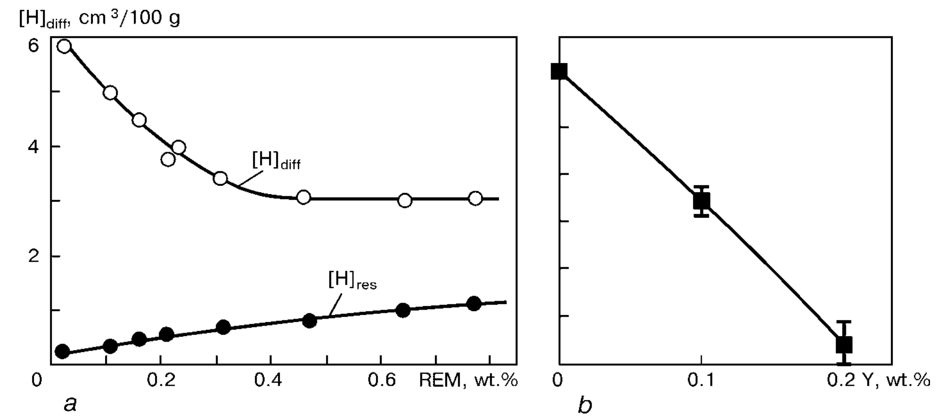

Figure 15. Effect of content of rare-earth metals (*a*) and yttrium (*b*) on concentration of diffusive hydrogen in metal of welds [10, 11] made by welding in mixture 0.1 % H_2 + Ar

welding consumables the heat treatment of electrodes and fluxes, drying of shielding gases are mainly used. Methods of reduction of hygroscopicity of coatings and vacuum packing of electrodes have been developed. Content of potential hydrogen in consumables should be reduced to minimum. Temperature of electrode baking is limited by 450 °C. Its further increase leads to the dissociation of coating components. In mixtures of minerals the temperature of dissociation beginning can be lower than that in initial minerals.

One of main sources of hydrogen enter is the dry remnant of a liquid glass. By adjusting modulus and viscosity of the liquid glass it is possible to decrease significantly the potential content of hydrogen in the electrode coating (flux). A large amount of hydrogen is evolved from the minerals at temperature exceeding the temperature of baking of electrodes and fluxes. In this case, to reduce the hydrogen concentration in weld metal several metallurgical methods, based on hydrogen binding in the arc atmosphere into hydroxyl OH and hydrogen fluoride HF, insoluble in molten steel, were suggested. The calculations showed that the adding of silicon tetrafluoride SiF_4 into a gas phase is more effective than the adding of a molecular oxygen. Silicon tetrafluoride is formed in interaction of CaF_2 with SiO_2. Calculations of a partial pressure of SiF_4 for CaF_2–SiO_2 system are given in [19]. This work contains also experimental data about the hydrogen concentration in weld metal deposited with electrodes having different amounts of CaF_2 and SiO_2 in the coating. A good correlation is observed between the partial pressure of SiF_4 and hydrogen concentration. The way of hydrogen concentration by adding silicon fluorides into the coating (flux) and flux-cored wire core is much more effective.

Consumables for welding HSLA steels. Elements composition of weld metal is selected usually coming from the requirements of producing welded joint having a strength equal to that of the parent metal. The most important task is the assurance of high cold resistance of metal of welds at temperatures down to –60 °C. Several systems of weld metal alloying are accepted: Cr–Ni–Mn–Cu–Mo; Mn–Ni–Ti; Mn–Ni–Mo–Ti. The content of these elements depends on the required strength and ductility of the welded joint. Microalloying with boron and titanium are used. Very pure welding wire for welding high-strength steels is used as to the content of sulphur and phosphorus (0.01–0.02 %), a mass share of carbon in it is 0.04–0.08 %. The content of alloying elements and deoxidizers, as well as welding conditions should be selected so that to provide the mass share of oxygen in weld metal within the ranges of 0.02–0.04 %. Titanium oxides, for example TiO, forming in this case, are the centers of origination of ferrite needles [20]. The structure of the acicular ferrite is favourable to produce weld metal being tough at low temperatures.

Interrelation between the chemical composition, structure and properties of metal of welds made on HSLA steels is described comprehensively in works

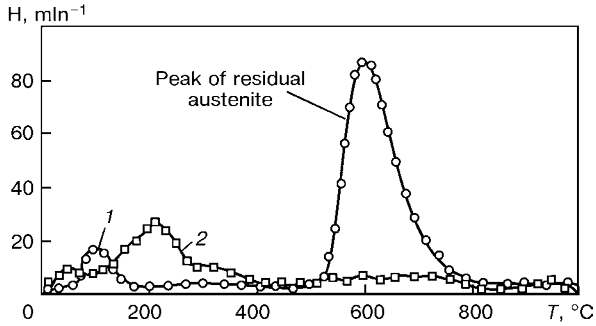

Figure 16. Thermodesorption analysis of redistribution of hydrogen (H) in metal of weld made on HSLA steels at phase transformations [18]: *1* — cooling of weld metal in air; *2* — the same in liquid nitrogen

[21, 22]. Characteristics of some electrodes are given in [23–28].

Highly-basic agglomerated fluxes and electrodes with a basic coating are used for welding. In welding HSLA steels with a mass share of 0.1–0.2 % C the preheating of products is required. The initiation of hydrogen-induced cracks is often observed in HAZ metal. The problem of creation of joints, not subjected to cracking, is tried to be solved by the development of steels with an ultralow (to 0.02 wt.%) content of carbon and more high degree of alloying. In welding structures from these steels the hydrogen-induced cold cracks will be formed in weld metal. The solution of this problem is associated with the development of reliable methods of control of hydrogen behaviour in the welded joints.

Owing to fundamental investigations of phenomena of reversible hydrogen embrittlement, carried out at the PWI [15–17], a mechanism of this process was studied at an atomic level.

The trends of further investigations can be formulated as follows:

- study of heterophase interactions which occur in heating and melting of electrodes, fluxes and flux-cored wires;
- decrease in hydrogen concentration in welded joints by decrease in content of hydrogen compounds in slag systems and control of plasma-chemical reactions in the arc atmosphere;
- increase in resistance of metal of weld and HAZ to the hydrogen embrittlement;
- physical and mathematical modelling of hydrogen behaviour in welded joints;
- control of condition of welded joints to prevent the cold crack formation, including creation of hydrogen «traps»in weld metal to decrease the concentration of diffusive hydrogen and limitation of its mass transfer from the weld metal to HAZ;
- development of fundamentals for producing metal of weld and joints with high strength, ductility and impact toughness;
- updating of equipment and technology of production of high-quality welding consumables of general and special purpose.

General-purpose electrodes. Today, the main steels which are used in industry and construction in

CIS countries, are low-carbon and low-alloy steels. General-purpose electrodes with rutile and ilmenite coatings occupy 80 % of electrodes produced. It should be noted that the *mechanical properties* of welded joints, made by these electrodes, satisfy the requirements of national, European and US standards. These electrodes should be improved as regards to stability of arc burning, formation of welds, removal of slag crust, prevention of pores and hot cracks. These problems are described comprehensively in review [29].

Adding of easily-ionizing elements into the coating leads to the increase in concentration of positive ions in the arc periphery zone, decrease in its constriction and reduction in work function of electrons from cathode. In this case the necessary density of current electrons can be attained at a lower intensity of electrical field near the cathode.

Removal of slag crust is defined greatly by the processes of slag interaction with a weld pool solidified metal. At the metal–slag interface a thin interlayer is, as a rule, formed, representing a non-stoichiometric oxides or spinels. If the values of parameters of a crystalline lattice of these joints are close to those of metal, then the chemical adhesion and epitaxial growth of a slag phase occurs, the slag removal in this case is deteriorated. It is possible to control this process by changing oxygen activity in the slag. In case of a poor weld formation, presence of undercuts the mechanical sticking of slag is occurred with a deterioration of its removal.

Problems of porosity are described comprehensively in [30]. It is shown here, that the porosity of welds in welding with electrodes of this type is caused by hydrogen dissolved in the weld pool. Hydrogen concentration in the weld pool is significantly higher than the equilibrium concentration, therefore, it is possible to prevent the pore formation in this case by control of the interphase tension at the metal–gas interface. The increase in oxidizing potential of metal is rather effective that makes it possible to reduce the probability of gas bubbles origin. One more method of prevention of pores formation is the control of the rate of growth of hydrogen bubbles by reduction in silicon content in the weld pool.

Formation of hot (crystalline) cracks in welds of low-carbon and low-alloy steels is associated, as a rule, with increase in carbon and sulphur content in the weld pool [31]. The sulphur source is the parent metal, welding wire and coating components. In national general-purpose steels the higher content of sulphur is allowed than in foreign steels (the same refers to the welding wires). It is possible to prevent the formation of hot cracks in welds by increasing a mass share of manganese in the deposited metal up to 0.6–0.8 %.

Electrodes with a basic coating are used, as a rule, for welding critical structures made from steels of different types. Problems of improving the welding-technological properties of electrodes and mechanical properties of welded joints were considered above.

One of the serious defects in welding with basic electrodes is a «start» porosity of welds. The investigations carried out showed that the appearance of this defect is caused by the nitrogen absorption by drops of electrode metal and weld pool. In welding under the basic slags containing fluoride compounds, the molten metal of drop and metal pool, poorly protected by the slag, contact directly the arc discharge plasma. Under the conditions of a thermodynamic equilibrium, a dissociation of gas molecules at the metal surface is a limitimg link in the process of absorption. In absorption of gases from arc discharge plasma the degree of dissociation of gases is defined by the plasma temperature.

The results of investigations carried out showed that the heat content of electrode metal drops depends on current and its polarity [19]. In many cases the temperature of drops exceeds the temperature of a maximum solubility of gases in iron. Therefore, the difference in drops at 200–300 K in welding with consumable electrode at straight and reverse polarity of current can greatly influence the absorption of gases. The higher content of gases in metal observed in practice in case of welding at alternating current of straight polarity, confirms this statement.

Nitrogen absorption depends on the arc length. The decrease in arc length by deposition of electroconductive compositions on the edge and electrode edge sharpening make it possible to shorten the arc length at electrode detachment at the moment of arc striking. The nitrogen absorption can be reduced by the decrease in interphase tension at the slag–metal interface to improve the slag protection of the molten metal at the stage of drop and pool, increase in temperature of drops and obtaining fine-drop or spray metal transfer at the expense of transition from the arc discharge in gases to the vapour-gas discharge. The same phenomena are observed in interaction of metal with hydrogen. Physical-chemical aspects of this process were considered above.

The most important problems requiring the solutions in the development of basic electrodes are as follows: improvement of welding-technological properties; increase in impact toughness of welded joints by reducing the content of harmful impurities and microalloying; decrease in hydrogen concentration in weld metal by prevention of moisture absorption in use of non-hygroscopic types of raw materials; application of high-modular low-viscous liquid glasses; optimizing of baking temperature and providing of a uniform temperature and humidity in drying-baking furnaces.

Investigations directed *to the improvement of hygienic characteristics* of electrodes are most important. The results of works carried out at the PWI in collaboration with hygienists, toxicologists, chemists, biophysicists are generalized in [32].

The main statements of these investigations can be formulated in the following way [33]:

• main toxic ingredient in fusion welding is a hard component of welding aerosol (HCWA);

• HCWA is formed as a result of evaporation of metal and slag melts, elements with a high pressure of vapour are evaporated more intensively;

• in melting electrodes with rutile and ilmenite coatings the evaporation of manganese from metal melt is by an order higer than from the slag melt;

• evaporation of elements and compounds from the slag depends on its basicity, with increase in the latter the compounds of alkali and alkali-earth metals are evaporated intensively;

• sanitary-hygienic characteristics of electrodes with rutile and ilmenite coatings can be improved by decrease in slag basicity and interphase tension at the metal–slag interface;

• overheating of electrode metal drops, welding pool and slag promotes the increase in amount of formed HCWA, temperature of molten metal and slag can be reduced by increase in coefficient of coating mass and increase in content of iron powder in it;

• in melting basic electrodes a gas component is of great importance, except the evaporation of manganese (chromium), which can represent fluoride compounds of alkali and alkali-earth metals, and also HF and SiF_4; evolution of these gases can be regulated by control of activity of silicon oxide in slag and content of moisture in the coating;

• limiting-allowable concentration of harmful elements in HCWA was established without taking into account peculiarities of structure, composition and size of its particles; combined action on the organism of group of elements of complex compounds can weaken or increase the effect of most toxic components of the welding aerosol;

• it is necessary to continue and intensify the works on modelling and prediction of a biological effect of HCWA on the human organism taking into account the results of integrated investigations made in the 1980–1990s.

Welding wires. *Solid wires.* This paragraph includes steel welding wires which are used for manufacture of coated electrodes for mechanized arc welding in shielded gases and under fluxes, electroslag welding as filler rods in non-consumable electrode welding.

Steel for wires is melted in basic oxygen furnaces, open-hearth and electric arc furnaces and poured either into ingots or billets in the machines of continuous casting of billets. In some cases the steel for manufacture of wires is subjected to a special treatment to decrease the content of harmful impurities, non-metallic inclusions and metal degassing. Ingots (billets) are rolled using the traditional technology. The rolled wire is subjected to cold deforming by drawing. Requirements for the wire are regulated by standard GOST 2246–70 which has become already old.

The solid wires will be further developed by updating their composition to improve the welding-hygienic properties, metallurgical characteristics of the welding process and improving properties of welded joints, namely minimizing of content of harmful impurities (sulphur, phosphorus, arsenic, antimony etc.); microalloying with titanium, strontium, boron, rare-earth metals etc.; decrease in mass share of carbon in some grades of high-alloy wires; optimizing systems of alloying; decrease in content of gases in wire; increase in homogeneity of billet and decrease in allowable deviations of elements content from the rated composition. Those billets are preferable which are produced from BOF steel in the machines of continuous casting of billets.

High ductility of the billets is necessary to increase the reliability of the drawing process, to provide mechanical properties of wires, high-quality and clean their surface without tears and scores, absence of ovality, minimum deviations of sizes of billets from the preset values.

Flux-cored wires. The industrial production of flux-cored wires in the USSR was created in the 1950–1960s and since that time was progressing intensively. The flux-cored wires were used effectively in some branches of industry and construction. The level of developments was high enough, that is proved by numerous author's certificates and patents, and also selling of our licenses abroad and organizing their production in several countries, such as the USA, Germany, France, Japan, Hungary, Bulgaria and others. Characteristics of these wires and specifics of technology of welding are given in catalogue [34].

Disintigration of economy in the 1990s led to the drop in the production level. Now the flux-cored wires are manufactured in old capacities of corporations «Severstal» in Russia and «Dneprometiz» in Ukraine. The preserved equipment is under the service until its full exhaustion. Those wires are manufactured which were developed as far back as the 1970–1980s. Meanwhile, this progressive trend of welding engineering is successfully progessing in such countries as the USA, Japan, France, Germany, South Korea, Sweden, Holland, Austria and others. The new grades of wires were developed there, the fields of their application were widened and the equipment and technology of manufacture were updated. For example, Lincoln Electric, Hobart, ESAB, SAF-Oerlikon, Thyssen Böhler, Kobelko, Elga and other companies manufacture dozens of grades of flux-cored wires for welding in CO_2 and Ar + CO_2 mixture, and also the self-shielding wires and wires for submerged arc welding. These types of welding consumables are designed for welding low-carbon, low-alloy, heat-resistant, high-strength, high-temperature, stainless steels used in shipbuilding, machine-building, power engineering, mining industry, construction and other branches [33–39].

It should be noted that the developments of the flux-cored wires in the above-mentioned years were fulfilled in several organizations of Ukraine and Russia. At the PWI the flux-cored wires of the new gen-

Table 2. Mechanical properties of metal of welds made by flux-cored wires

Wire grade	*Yield strength, MPa*	*Ultimate rupture strength, MPa*	*Elongation, %*	*Temperature (°C), providing required level of impact toughness**	*Slag characteristic*
PP-AN59	420	550–600	24–28	–20	Quickly-solidified on rutile base
PP-AN63	420	520–560	25–29	–20	Same
PP-AN69	420	510–540	28–33	–30	Basic
PP-AN61	460	550–630	23–25	–40	On rutile base
PP-AN67	560	700–760	18–20	–30	Basic

*Impact energy was not less than 47 J.

eration were created in accordance with the European standard EN 758 and GOST 262–71 [40].

For welding general-purpose carbon and low-alloy steels the following grades of wires were developed: PP-AN59, PP-AN63, PP-AN69, for welding HSLA steels — PP-AN61, PP-AN67. These wires have a tubular design and diameter from 1.2 up to 2.0 mm. Their characteristics are given in Tables 2 and 3.

Welds made by welding using new wires are characterized by a good shape, small amount of spatters and aerosols. During melting the rutile wires of the PP-AN59 and PP-AN63 types form quickly-solidified short slags. They are suitable for welding in all spatial positions. Wire PP-AN70 with a metallic core was developed for the automatic and robotic welding in CO_2 used in shipbuilding and machine-building. Surfacing efficiency in use of this wire is by 20 % higher than that in use of the solid wire of the same diameter. This wire has much higher welding-technological properties as compared with wire Sv-08G2S.

At the PWI the self-shielding flux-cored wires with a fluoride-basic core have been developed [41]. Owing to this composition of the core the content of silicon and aluminium in metal of welds is decreased and the required impact toughness of welded joints at low temperatures is provided.

TsNIIKM «Prometej» carries out work for creation of gas-shielding flux-cored wires of 48-PP-8N, 48-PP-11R, 48-PP-12R grades of 1.2–1.6 mm diameter for welding low-carbon HSLA steels with yield strength from 400 up to 620 MPa [42]. At the present time, the technology of welding with these wires is under the experimental-industrial trials at shipbuilding yards of Russia, and the technology of manufacture of wires is also improved. At OJSC «NIImontazh» the self-shielding flux-cored wires have been developed for welding in all spatial positions providing weld metal with yield strength up to 490 MPa [43].

It is most important to create the updated high-efficient equipment and technology of manufacture of small-diameter flux-cored wires for the further development of the flux-cored wires. Over the recent years a method of manufacture of flux-cored wires by rolling-drawing has been advertized. Wires manufactured by this technology have a remained thin layer of drawing lubricant at the surface, owing to which a high content of hydrogen is not entrapped into the arc atmospere during mechanized welding, and a good wire feeding along the flexible hoses is provided.

At the PWI, in collaboration with its Pilot Plant of Welding Consumables and Heavy Machine-Building Works in Almaty, an advanced equipment and technology of manufacture of small-diameter flux-cored wires have been developed. Set of equipment for main operations of production is furnished with modern units of objective control, documenting of technological operations and diagnostics [44]. The new equipment with a design capacity of 1000 tons per year was delivered to the plants of China. The attained capacity 1.5 times exceeded the desgin capacity. Thus, all the conditions have been created for the production of new wires at the plants of Russia and Ukraine. A comprehensive analysis of the market and appropriate financing of this project are required.

Technology and equipment have been developed for manufacture of 9–13 mm diameter flux-cored wires for injection metallurgy. The industrial manufacture of these wires was implemented at the Company «Arcsel» and at the PWI Pilot Plant of Welding Consumable. Using this technology during recent

Table 3. Chemical composition of metal (wt.%) deposited with flux-cored wires*

Wire grade	*C*	*Mn*	*Si*	*Ni*	$[H]_{diff}$ *in deposited metal, cm³/100 g*
PP-AN59	0.05–0.08	1.1–1.5	0.3–0.6	0.4–0.6	5–8
PP-AN63	0.04–0.07	1.2–1.6	0.3–0.5	–	5–8
PP-AN69	0.07–0.09	1.3–1.5	0.3–0.4	–	4–7
PP-AN61	0.03–0.07	1.1–1.5	0.3–0.5	1.3–1.7	3–5
PP-AN67	0.04–0.09	1.1–1.3	0.3–0.4	1.1–1.3	3–5

*Mass share of chromium and molybdenum is 0.2–0.4 %.

years at «Azovstal», Iljich plants and other industrial enterprises the millions of tons of different-purpose steels were treated and a significant improvement of their quality was attained. The steels produced were certified by most insurance agencies of the world. Application of flux-cored wires is challenging. Specialists of Ukraine and Russia have enough knowledge and experience to revive the advanced production of these materials.

Welding fluxes. The method of submerged arc welding, developed during the pre-war years at the PWI, has found a wide spreading in our country in shipbuilding, machine-building, in construction of bridges, fabrication of building metal structures, etc. The high level of scientific developments, progressive metallurgical solutions, well-organized industrial manufacture, low cost of power suppliers ensured the mass production of inexpensive high-quality fused fluxes. As to the volumes of production of fused fluxes the USSR occupied the first place in the world. The application of SAW caused revolutionary reorganizations in many branches of industry and construction.

At present the production of welding fluxes in the industrialized countries has been stabilized. The output of consumables for SAW is 5–10 % of the total volume of welding consumables. Metallurgical and technological peculiarities of SAW are described in many specialized publications [31, 45–49].

The reduction in consumption of steels caused, naturally, the multiple reduction in production of fused fluxes, and, first of all, energy-consuming production of fluxes in electric furnaces.

The works of the recent years were devoted to the decrease in content of harmful impurities in fluxes, searching for advanced flux–wire systems, providing the necessary mechanical properties of welded joints, decrease in content of hydrogen in fluxes [49–53].

As was above-mentioned, the growth of production of HSLA steels is observed in the world. It is very difficult to satisfy the high requirements to the mechanical properties of welded joints using the fused fluxes. The investigations showed, for example, that in welding HSLA steel of 12KhN2MDF type, used for manufacture of critical structures operating on a continental shelf, with alloyed wire, produced by a vacuum induction melting under flux FIMS-20P, the required level of impact toughness is provided only at test temperature −20 °C, while that at −60 °C is provided under agglomarated flux [54].

In countries of West Europe the fused fluxes were replaced during recent decades by agglomerated fluxes, which amount to 95 % of all the volume of consumed welding fluxes [55]. This is explained by a number of metallurgical possibilities of agglomerated fluxes, such as control of silicon-reduction process, refining and microalloying of weld pool, high strength and impact toughness of the welded joints. The application of welding fluxes ensures the several times reduction in energy-consuming of production, promotes the decrease in harmful exhausts of toxic dust and gases into atmosphere. Information about modern agglomerated fluxes, and also the description of the technology of their production are available in [54, 56–58].

In connection with the development of manufacture of modern pipes, shipbuilding, power and chemical machine-building, construction of bridges in Russia and Ukraine, the volumes of application of HSLA steels will be, undoubtedly, increased. Even today it is necessary to create the industrial models of equipment and technology of production of these fluxes, to certify the ready developments, to make marketing and to organize the export of products.

CONCLUSIONS

Efforts of researchers and developers should be concentrated on the search for new types of raw materials and creation of the following new welding consumables:

- general-purpose electrodes with rutile and ilmenite coatings having excellent welding-technological and hygienic properties;
- electrodes of the new generation for welding HSLA steels for shipbuilding, machine-building, construction;
- general-purpose electrodes with a basic coating providing impact toughness of welded joints of not lower than 60 J/cm^2 at test temperature −60 °C;
- electrodes for welding site butt joints of modern main pipelines;
- wires and agglomerated fluxes for welding HSLA steels with up to 800 MPa yield strength;
- flux-cored wires with rutile and basic core and small-diameter wires with a metallic core for shielded-gas welding in all spatial positions;
- versatile self-shielding flux-cored wires;
- special different-purpose welding consumables.

Investigations and developments of the new high-effcient equipment and technologies of manufacture of welding consumables, systems of analytic accompanying and management of quality of products should become priority.

At the first quarter of the XXI century the steel will remain to be the major structural material. Low-carbon and low-alloy steels will be still widely used. Their quality, mechanical properties and weldability will be improved by reduction of harmful impurities, search for new systems of alloying, heat treatment, increase in corrosion resistance in different media. New types of HSLA steels will be rapidly developed, including those with ultralow content of carbon, heat-resistant steels, steels for structures operating at low climatic temperatures, and also for cryogenic engineering, different-purpose high-alloy steels. Aluminium high-strength alloys, alloyed titanium alloys and other types of new structural materials will be further developed.

The arc welding will still occupy the leading position among the existing methods of fusion welding. The progress in the creation and development of welding consumables depends on the tendency of the development of structural materials. The main solutions in the field of creation of new welding consumables will be connected with the optimizing systems of weld metal alloying depending on structure and properties of the parent metal, searching for the ways to decrease the content of hydrogen, nitrogen and other harmful impurities in metal of welds, development of effective materials and technologies, which will make it possible to increase the strength and ductility of the welded joints, to reduce the preheating temperature, to prevent the formation of different types of cracks including hydrogen-induced cracks.The search will be made for new slag systems of cores of flux-cored wires, electrode coatings and fluxes. Metallurgical and welding-technological properties of electrodes, fluxes, solid and flux-cored wires, shielding gases will be updated to reduce the porosity, to prevent crystalline cracks, to improve penetration, shapes of welds, removal slag crust, stability of arc burning and to decrease spattering.

Mathematical and physical modelling of main metallurgical processes of arc welding will be further developed. Computerized databanks and base of knowledge, expertise systems on different-purpose welding consumables will be created.

In the industrialized countries the share of output of coated electrodes will be also reduced in future in the total volume of production of welding consumables and the manufacture of solid wires for shielded-gas welding and especially flux-cored wires (with flux and metallic core) will be increased, the share of production of welding fluxes here will remain. The arc welding with coated electrodes will be still widely used in the developing countries. The researchers will have to work for the descrease in material and power content of welding consumables both in the process of their production and also in their application. The universal small-diameter gas-shielding flux-cored wires and agglomerated fluxes, effective in welding of special critical structures, will be mainly progressed. A great attention will be also paid to the creation of electrodes, fluxes and wires, absorbing minimum moisture and providing a good repeated exciting of arc, their easy «feeding» by welding semi-automatic and automatic machines, minimum evolution of welding arosols.

The further works will be also required in the direction of improvement and increase of reliability of equipment and technology of production of welding consumables, searching for raw materials of a stable quality, automation of analytical control and technological management of production. The quality of welding consumables, their marketable state, packing and transportation will be improved. It is necessary to prepare the different specialists: researchers and developers of welding consumables, and also technologists-manufacturers, highly-qualified technicians and workers.

The updating of the economical system, increase in competition from the side of countries of West and East will make us to increase the rates of economical-technical transformations and will promote the increase in production of welded structures and welding consumables to the new level.

1. Doria, J.G. (2001) *Welding consumables: Market trends.* Istanbul: European Welding Association.
2. Tikhonov, A. (2002) World war of steelmakers. *Izvestiya*, September 19.
3. Ignatchenko, P.V., Bugaj, A.I. (2001) State-of-the-art of welding consumables manufacturing at the threshold of the new century. In: *Arc welding. Consumables and quality at the threshold of the 21st century*. Proc. of 2nd Int. Conf. on Welding Consumables of CIS Countries, Oryol, June 4–8, 2001.
4. (2001) *The Japan Welding News for the World*, **17**, 10.
5. (2001) van Nassau, L. (2001) *Expert report stick electrodes 2000: Stick electrodes.* Istanbul: European Welding Association.
6. Morrison, W.B. (2000) Past and future development of HSLA steels. In: *Proc. of 4th Int. Conf. on HSLA Steels'2000*, Oct. 30 – Nov. 2, 2000. Beijing: Met. Ind. Press.
7. Gorynin, I.V., Malyshevsky, V.A., Legostaev, Yu.L. et al. (1998) Prospects and problems of materials science in development of welding consumables and technologies during construction of unique ice-resistant platforms. In: *Advanced materials science: The 21st century*. Ed. by I.K. Pokhodnya. Kyiv: Naukova Dumka.
8. Yurioka, N., Suzuki, H. (1990) Hydrogen assisted cracking in C–Mn and low alloy steel weldments. *Int. Materials Rev.*, **4**, 217–249.
9. Yurioka, N. (1999) Predictive methods for prevention and control of hydrogen-assisted cold cracking. *IIW Doc. IX-1938–99*.
10. Maroef, I., Olson, D.L., Edvars, G.R. (1998) Hydrogen-induced cracking of high-strength steel weldments. In: *Proc. of Int. Conf. on Welding and Related Technologies for the 21st Century*. Kyiv: PWI.
11. Pokhodnya, I.K. (1998) Problems of welding of high-strength low-alloy steels. In: *Advanced materials science: The 21st century*. Ed. by I.K. Pokhodnya. Kyiv: Naukova Dumka.
12. Shvachko, V.I., Stepanyuk, S.N., Pokhodnya, I.K. (2000) The evaluation methods of HSLA steels susceptibility to hydrogen embrittlement. In: *Proc. of 4th Int. Conf. on HSLA Steels'2000*, Oct. 30 – Nov. 2, 2000. Beijing: Met. Ind. Press.
13. Gedeon, S.A., Eagar, T.W. (1990) Assessing hydrogen-assisted cracking fracture modes in high-strength steel weldments. *Welding J.*, **6**, 213.
14. Gedeon, S.A., Eagar, T.W. (1990) Thermomechanical analysis of hydrogen absorption in welding. *Ibid.*, **7**, 264.
15. Pokhodnya, I.K., Stepanyuk, S.N., Shvachko, V.I. (2000) Role of temperature in hydrogen-induced cracking of structural steels and welded joints. *The Paton Welding J.*, **2**, 2–7.
16. Shvachko, V.I. (2002) *Reversible hydrogen embrittlement of bcc-alloys of iron-structural steels*. Syn. of Thesis for Dr. of Phys.-Math. Sci. Degree. Kharkiv: KhFTI.
17. Stepanyuk, S.M. (2001) *Reversible hydrogen embrittlement in welding of high-strength low-alloy steels*. Syn. of Thesis for Cand. of Techn. Sci. Degree. Kyiv: PWI.
18. Park, Y.D., Maroef, I.S., Landau, A. et al. (2002) Retained austenite as a hydrogen trap in steel welds. *Welding J.*, February, 19–35.
19. Pokhodnya, I.K. (2003) Mathematical modelling of processes of interaction of metals with gases in arc welding. *The Paton Welding J.*, **2**, 2–9.
20. Abson, D.J. (1987) Microstructure and mechanical properties of vertical-up C–Mn–Ni steel semi-automatic weld metal. *Welding Inst. Res. Rep.*, **7**, 1–30.
21. Baryshnikov, A.P., Grishchenko, L.V., Petrykin, V.I. (1996) Covered-electrode gas-shielded welding of high-strength cold-resistant steels. *Progr. Materialy i Tekhnologii*, **2**, 207–220.
22. Malyshevsky, V.A., Grishchenko, L.V., Baryshnikov, A.P. (1999) Consumables and technology of high-strength steels welding. *Voprosy Materialovedeniya*, **3**, 69–77.

23. Gezha, V.V., Baryshnikov, A.P., Grishchenko, L.V. et al. (2000) Means of improvement of welding-technological characteristics of basic electrodes designed for welding of high-strength and cold-resistant steels. *Ibid.*, **1**, 69–77.
24. Pokhodnya, I.K., Milichenko, S.S., Gorpenyuk, V.N. et al. (1990) ANO-TM electrodes for welding of stationary off-shore platforms. *Tekhnologiya Sudostroeniya*, **9**, 77–79.
25. Yavdoshchin, I.R. (1998) New electrodes of the PWI for welding of low-carbon and low-alloy steel structures. In: *State-of-the-art and prospects of development of welding consumables in CIS countries*. Proc. of 1st Int. Conf. on Welding Consumables of CIS Countries, Krasnodar, June 23–26, 1998.
26. Marchenko, A.E., Skorina, N.V. (1998) E70-E85 type electrodes for welding of high-strength cold-resistant steels. *Ibid*.
27. Lobanov, L.M., Mikhoduj, L.I., Poznyakov, V.D. et al. (1998) Sparsely-alloyed electrodes of E70-E85 types for welding of high-strength cold-resistant steels. *Ibid*.
28. Malyshevsky, V.A., Grishchenko, L.V., Baryshnikov, A.P. et al. (1998) Electrodes for welding of structures operating at low temperatures and necessity in improvement in their technological properties. *Ibid*.
29. Pokhodnya, I.K. (1998) Welding metallurgy, state-of-the-art and problems. In: *Proc. of Int. Conf. on Welding and Related Technologies for the 21st Century*. Kyiv: PWI.
30. Pokhodnya, I.K. (1972) *Gases in welds*. Moscow: Mashinostroenie.
31. Frumin, I.I. (1961) *Automatic wear-resistant hardfacing*. Kharkiv: Metallurgizdat.
32. Vojtkevich, V. (1995) *Welding fumes: Special report*. Abington.
33. Yavdoshchin, I.P., Pokhodnya, I.K. (2002) Formation of welding aerosol in fusion arc welding and its hygienic estimation. In: *Proc. of 1st Int. Sci.-Techn. Conf. on Protection of Environment, Health and Safety in Welding Production*. Odessa: Astroprint.
34. (1980) *Flux-cored wires for electric arc welding*. Catalogue-Refer. Book. Ed. by I.K. Pokhodnya. Kyiv: Naukova Dumka.
35. Altemuhle, B. (2000) The use of rutile cored wires for welding high-strength steel in crane fabrication. *Svetsaren*, **3**, 24–27.
36. Ferree, S.E., Sierdzinski, M.S. (2000) Stainless steel metal cored wires for welding automotive exhaust systems. *Ibid.*, 15–18.
37. Blome, K. (2000) Filarc PZ 6105R. The robot-friendly cored wire. *Ibid.*, **1**, 22–24.
38. Farrow, N., Studholme, S. (2000) Submerged arc welding with fused flux and basic cored wire for low-temperature applications. *Ibid.*, **1**, 33–36.
39. (1990) Fabshield 2125. *Welding J.*, **7**, 3–5.
40. Shlepakov, V.N., Rak, P.I., Kosenko, P.A. (2001) Flux-cored wire of new generation for gas-shielded welding. In: *Arc welding. Consumables and quality at the threshold of the 21st century*. Proc. of 2nd Int. Conf. on Welding Consumables of CIS Countries, Oryol, June 4–8, 2001.
41. Naumejko, S.M. (2001) Control of welding-technological properties of flux-cored wires according to data of physicochemical properties of slags. *Ibid*.
42. Baranov, A.V., Grishchenko, L.V., Baryshnikov, A.P. et al. (2001) Problems of manufacturing and experience of industrial applications of small-diameter flux-cored wires. *Ibid*.
43. Mojsov, L.P., Isaenko, P.R. (2001) Self-shielded flux-cored wire PPT-13. *Ibid*.
44. Shlepakov, V.N. (2001) Automated equipment for manufacture of flux-cored wire. *Ibid*.
45. Frumin, I.I., Rabkin, D.M., Podgaetsky, V.V. et al. (1956) Low-silicon fluxes for automatic welding and hardfacing. *Avtomatich. Svarka*, **1**, 3–20.
46. Lyubavsky, K.V. (1960) *Metallurgy of fusion welding*. Handbook on welding. Ed. by E.V. Sokolov. Vol. 1. Moscow: Mashgiz.
47. (1974) Welding fluxes and slags. In: *Proc. of Int. Seminar*, Nikopol, Sept. 1974. Ed. by B.E. Paton. Kyiv: Naukova Dumka.
48. Podgaetsky, V.V., Kuzmenko, V.G. (1988) *Welding fluxes*. Kyiv: Naukova Dumka.
49. Potapov, N.N. (1997) State-of-the-art and prospects of development of flux manufacturing. *Svarochn. Proizvodstvo*, **9**, 34–36.
50. Goncharov, I.A., Tokarev, V.S., Paltsevich, A.P. et al. (1998) Flux, limiting the hydrogen content in weld. In: *State-of-the-art and prospects of development of welding consumables in CIS countries*. Proc. of 1st Int. Conf. on Welding Consumables of CIS Countries, Krasnodar, June 23–26, 1998.
51. Goncharov, I.A., Paltsevich, A.P., Tokarev, V.S. (1998) About new approach to porosity prevention in welding under fused fluxes. *Ibid*.
52. Kuzmenko, V.G. (2002) *Thermodynamic and structural aspects of selection of fluxes for electric arc welding*. Syn. of Thesis for Dr. of Techn. Sci. Degree. Kyiv: PWI.
53. Goncharov, I.O. (2002) *Development of low-hydrogen welding fluxes of manganese-silicate type*. Syn. of Thesis for Cand. of Techn. Sci. Degree. Kyiv: PWI.
54. (2002) Welding and allied technologies at the Essen Fair. *The Paton Welding J.*, **1**, 27–41.
55. Pokhodnya, I.K., Kushnerev, D.M., Ustinov, S.D. et al. (1987) Results of comparison testing of fused and ceramic fluxes used in welding of 12KhN2MDF steel. *Avtomatich. Svarka*, **11**, 61–64, 68.
56. Pokhodnya, I.K., Golovko, V.V. (1999) Fluxes for welding of low-alloy high-strength steels developed in the PWI. *Svarshchik*, **1**, 8–9.
57. Baranov, A.V., Grishchenko, L.V., Baryshnikov, A.P. et al. (2001) Agglomerated fluxes for automatic welding of high-strength and cold-resistant steels and technology of its manufacture developed by TsNIIKM «Prometej». In: *Arc welding. Consumables and quality at the threshold of the 21st century*. Proc. of 2nd Int. Conf. on Welding Consumables of CIS Countries, Oryol, June 4–8, 2001.
58. Lakomsky, V.I. (1974) *Plasma-arc remelting*. Ed. by B.E. Paton. Kyiv: Tekhnika.

HIGH-VANADIUM ALLOYS FOR PLASMA-POWDER CLADDING OF TOOLS

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Structure, hardness and wear resistance of two groups of iron-base high-carbon high-vanadium alloys with a different chromium content (5–7 and 14–17 %) are considered. Among the high-carbon high-vanadium alloys, the materials with a martensitic structure and a small amount of retained austenite, as well as with dispersed, uniformly distributed vanadium carbides and carbides of the $Me_{23}C_6$ type, were found to have the highest wear resistance under the abrasive wear conditions.

Key words: *high-carbon high-vanadium alloys, cladding powders, plasma-powder cladding, wear resistance*

Different industries experience the need to cut non-metallic materials, such as wool, paper, cardboard, leather and other materials of a vegetable or animal origin. Performance of tools for cutting non-metallic materials depends primarily upon the resistance of their cutting edges to spalling and abrasive wear. There are cases, for example, knives for industrial meat grinders, where corrosion resistance of a material plays an important role. Spalling of the cutting edges can be avoided if metal a knife is made from has a fine-grained structure with a dispersed, uniformly distributed reinforcing carbide phase. At the same time, the fraction of the carbide phase in metal structure should be as high as possible, as this determines the abrasive wear resistance of tool steels and alloys. Corrosion resistance of knives can be provided at a high hardness maintained by alloying the material with chromium (more than 12 %) [1].

Cladding is widely applied at present to save expensive tool steels in the manufacture of different types of tools, including knives for cold and hot cutting of different materials [2]. In general, the tool bodies are made from relatively inexpensive structural steels, while their working edges or working surfaces are made from tool steels.

Basic alloying elements for tool steels and alloys are tungsten, molybdenum and chromium, which form comparatively coarse (up to 50 μm) carbides during cladding. It is this factor that leads to spalling of the working edges of knives. In contrast to the above elements, vanadium, forming very fine and, at the same time, hard and wear-resistant carbides, is a highly promising alloying element for tool steels and alloys intended for cladding of tools for cold cutting of non-metallic materials [3–5].

In electrode and filler materials designed for arc surfacing, the use of vanadium as an alloying element is hindered by its ability to form spinels, the latter making the slag crust hard-to-detach. For this reason, the mass fraction of vanadium in flux-cored wires for arc surfacing of tool steels is limited to 0.5 % [2]. Plasma-powder cladding in a shielding atmosphere of inert gases opens up wider possibilities in terms of alloying the deposited metal with vanadium.

Fe-base alloys in the form of powders with a design vanadium content of up to 20 and carbon content of up to 4.5 wt.% were studied in order to develop a new class of cladding consumables for treatment of knives for cold cutting of non-metallic materials. Powders for cladding were atomised in nitrogen.

In the first group of powders of alloys No.1–3 (Table) intended for cladding of tools for cutting non-metallic materials having no corrosion-resistant properties, the design content of chromium was 5.0–6.5 %. In addition, in this group of the alloys the vanadium content was varied approximately from 10 to 20, and the carbon content was varied from 2.6 to 4.2 %. In the second group of powders (No.4–6) to be used for cladding of knives with increased corro-

Chemical composition, hardness and wear of the studied Fe-base high-carbon high-vanadium alloys

Alloy No.	*Content of elements, wt.%*							*Hardness, HRC*	*Wear, mg*
	C	*Mn*	*Si*	*Cr*	*V*	*Mo*	*Ni*		
1	2.59	0.82	0.98	5.50	10.30	1.30	–	60–63	14.40
2	3.70	0.76	1.14	5.17	13.40	1.02	–	55–58	5.60
3	4.23	1.07	1.15	6.43	20.20	1.30	–	60–62	4.40
4	4.25	1.76	1.43	16.72	15.18	1.97	–	50–53	7.65
5	4.45	1.01	0.64	16.03	14.66	2.00	1.08	60–62	6.42
6*	4.68	1.00	0.80	14.15	14.91	2.10	1.30	55–58	6.42

*In alloy No.6 the niobium content is 1.05 %.

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sion-resistant properties, the vanadium content was 14–17 wt.%, and the chromium and carbon content in each of these alloys was kept at the same level (≈ 15.0 and 4.5 wt.%).

For tool steels it is very important to select the optimal proportion of carbon and carbide-forming elements. Depending upon the stoichiometric composition of carbides, the following mass fraction of carbon is required per each percent of vanadium contained in steel: V_4C_3 — 0.175, V_6C_5 — 0.196 and VC — 0.236 %. To ensure the best combination of properties of an alloy, it is desirable that the vanadium to carbon ratio in it be within a range of 3.5 to 4.0 [6]. At the presence of other carbide-forming elements in steel, the mass fraction of carbon should be such that it is enough to form the corresponding carbides and harden the matrix.

Chromium and molybdenum do not only participate in formation of carbides. Also, they make alloys susceptible to quenching and provide the martensitic base. Silicon and manganese are added to alloys as deoxidisers.

Alloys No.5 and 6 were additionally doped with nickel. It was expected that this should lead to formation of an extra amount of retained austenite in structure of the alloys and increase their corrosion-resistant properties. Alloy No.6 was also doped with niobium, which enabled estimation of properties of this alloy in the presence of another strong carbide-forming element.

Given that the future plans are to use experimental alloys for the manufacture of different-application bimetal knives, experiments were conducted to study hardness, wear resistance and structure of the deposited metal with chemical composition corresponding to that of the experimental alloys.

The experiments began with studies of welding-technological properties of high-carbon high-vanadium alloys. Cladding was performed by the plasma-powder method, and steel St.3 was used as the base metal. Groove for cladding was made in the plates, the size of the groove corresponding to that in an actual tool for cutting non-metallic materials. The most important parameters of plasma-powder cladding are arc current I_a, cladding speed v_c and powder feed speed [7, 8]. The following cladding conditions were used in the experiments: I_a = 140–280 A and v_c = 2.0–5.3 m/h.

As the cladding speed was increased, the powder feed speed was increased accordingly (to keep a cross section of the deposited bead constant), and the frequency of periodic oscillations of the plasmatron was raised so that the cladding pitch remained equal to approximately 1.5 mm. The amplitude of oscillations of the plasmatron was set 1–3 mm larger than the groove width. The flow rates of plasma, transportation and shielding gases in all the experiments were kept constant. To compare, deposition of Co–Cr–W alloys, i.e. stellites, widely applied for cladding of cutting tools, was conducted simultaneously with deposition of the experimental high-carbon high-vanadium alloys.

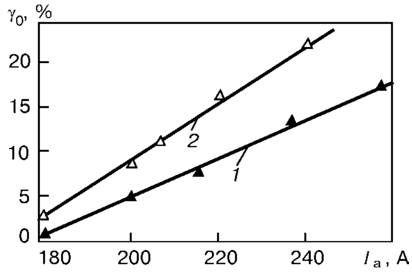

Figure 1. Effect of arc current I_a on the base metal content, γ_0, of a layer deposited with different alloys at v_c = 3.7 m/h: *1* — high-vanadium alloy; *2* — stellite

The main purpose of the technological experiments was to determine the optimal range of values of the arc current at different deposition efficiencies. In this case the lower limits of the I_a values were estimated from a condition of producing the guaranteed defect-free fusion of deposited beads with the base metal at a preset cladding speed, whereas the lower limits were estimated from a condition of producing the base metal content of the deposited metal not higher than 10 %. The effect of the arc current on the base metal content of the deposited layer was studied to determine its maximum permissible values (see Figure 1).

The base metal content of the deposited metal varied from 0 to 25 % within the investigated range of the process conditions. In a range of low values of the current its increase of 10 A led to an increase of 2–5 % in the base metal content of the deposited metal.

Optimal values of the arc current at different cladding speeds are given in Figure 2. Beads deposited under the recommended conditions are characterised by good formation and constant width and height.

Despite the fact that cladding of the high-carbon high-vanadium alloys was conducted without preheating, no case of cracking and porosity was noted in the deposited metal.

Compared with stellites, the high-carbon high-vanadium alloys are more cost-effective and more practicable, as they can be deposited at lower values of the arc current (see Figures 1 and 2).

The method with a fixed abrasive was chosen to estimate wear resistance of the high-carbon high-vanadium alloys. The test conditions were as follows: abrasive — corundum cloth with a grit size of 180 μm, friction area 1 cm^2, load 30 N and test time 20 s. Wear resistance was estimated on the basis of loss in weight of the test specimens.

The Table gives results of wear resistance tests of alloys No.1–6 deposited under the optimal conditions. To compare, it should be noted that the widely known

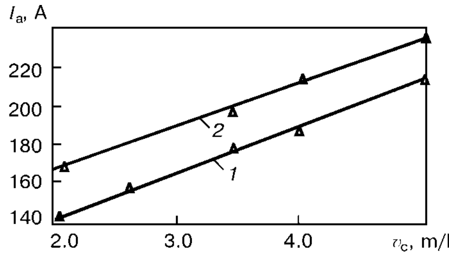

Figure 2. Variation in arc current I_a depending upon the cladding speed v_c (*1*, *2* — see Figure 1)

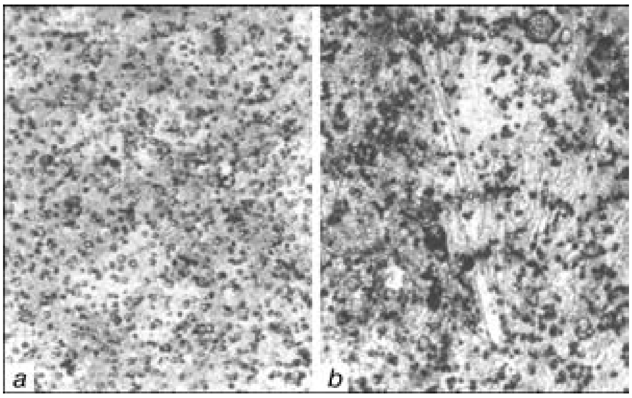

Figure 3. Microstructure of high-carbon high-vanadium alloys No.2 (*a*) and 5 (*b*) (×320)

tool steel R6M5F2 tested under the same conditions had a weight loss of 19.2 mg, and a hard alloy of the VK8 type had a weight loss of 1.6 mg. As seen from the data given, the high-carbon high-vanadium alloys take an intermediate position in wear resistance between tool steels and hard alloys, but they are much less expensive than the latter.

Of all the high-carbon high-vanadium alloys tested, alloy No.1 with a decreased carbon and vanadium contents, compared with other materials, had the worst wear resistance. It is likely that the mass fraction of vanadium should be not less than 13 % and that of carbon — not less than 4 % to ensure a high wear resistance of materials. Alloys No.2 and 3 with a mass fraction of chromium equal to 5.0–6.5 % had the best wear resistance. Of alloys with an increased chromium content, the best wear resistance was exhibited by alloys No.5 and 6 (see the Table).

Microstructure of the high-carbon high-vanadium alloys was studied. Samples for metallography were cut from the St.3 plates 18 mm thick deposited with powders of experimental alloys No.1–6 under the following conditions: I_a = 180–200 A, v_c = 3.5 m/h, and air cooling after cladding. According to the metallography data, structure of the high-carbon high-vanadium alloys consisted of carbides, martensite and retained austenite. The amount of retained austenite in the alloys studied may vary, which affects their hardness and wear resistance. Figure 3 shows a characteristic microstructure of high-carbon high-vanadium alloys No.2 and 5.

Formation of structure during solidification of the high-carbon high-vanadium alloys can be described as follows. Vanadium carbides are the first to precipitate from the melt and are the nuclei with an austenite depleted in alloying elements being solidifies around. The precipitation process is accompanied by transformation of austenite into martensite. External regions of grains consist of a high-alloy austenite which retains during cooling to room temperature.

Structure of all the alloys studied is characterised by a sufficiently uniform distribution of each of the structural components across the section of the deposited bead. Width of the transition zone between the deposited and base metals is 0.01–0.20 mm.

As a rule, high wear resistance under abrasive wear conditions is characteristic of multi-component carbide-reinforced alloys having high hardness. In this case the matrix of such alloys should also be capable of retaining strong and hard carbides during wear, in addition to having a high hardness.

It is suggested in [9] that carbides can be strongly retained by the matrix if a bond of the crystalline lattices at the carbide–matrix interface is formed during solidification.

X-ray diffraction analysis of specimens of the deposited metal of the type of the high-carbon high-vanadium alloys was conducted using the DRON-3 instrument to determine the crystalline lattice parameters. Lines (211) in α-iron and (311) in γ-iron were selected to measure the above parameters. Design error of estimation of the lattice parameters was ± 0.0003 for α-iron and ± 0.0002 for γ-iron within the selected ranges of the reflection angles. Size of the lattice of α-iron in the alloys studied was (0.2864–0.2867) ± 0.0003 and that of γ-iron was (0.3587–0.3599) ± 0.0002 nm. Size of the crystalline lattice of vanadium carbide VC, according to the data of [4], was 0.4135–0.4166 nm.

The data of X-ray diffraction analysis are indicative of matching of the crystalline lattices of vanadium carbide and austenite, and vanadium carbide and martensite seen along some crystallographic orientations:

(011)VC || (111) γ-Fe <011>VC || <111> γ-Fe

(001)VC || (011) α-Fe <001>VC || <011> α-Fe.

Calculations made on the basis of these data showed that difference in the crystalline lattice parameters along the above orientations was no more than 5 % for vanadium carbide and austenite and 2 % for vanadium carbide and martensite.

In this case a strong bond of the crystalline lattices, i.e. cohesion, can be formed at the austenite–carbide and martensite–carbide interfaces [10]. Real vanadium carbide particles are not single crystals. Therefore, a strong bond is formed only in individual regions of their surfaces, where there is a favourable orientation of vanadium carbide and austenite grains, as well as of vanadium carbide and martensite grains.

According to the data of X-ray microanalysis (Figure 4) vanadium forms carbide VC in the deposited metal, whereas the vanadium content of other structural components is negligible. Size of vanadium carbides varies from 2 to 10 μm. Chromium is part of the matrix and complex carbides of the type of $Me_{23}C_6$ and Me_7C_3 (Figure 4, *c, f, i*). Coarse-acicular carbides of the type of Me_7C_3 are formed only in alloys which contain a redundant amount of carbon (Figure 4, *g*–*i*).

Structural components of the investigated alloys have the following microhardness $HV_{0.05}$: carbides of the type of VC — 2900–3000, carbides of the type of $Me_{23}C_6$ — 900–1300, martensite — 800–900 and austenite — 600–700.

Of the first group of the alloys (No.1–3), the most promising alloy is alloy No.2. It is somewhat inferior in wear resistance to alloy No.3. But compared with the latter, it is more practicable in manufacture and cladding.

Of the second group of the alloys (No.4–6), alloys No.5 and 6 have high wear resistance. Investigations of microstructure and X-ray microanalysis showed

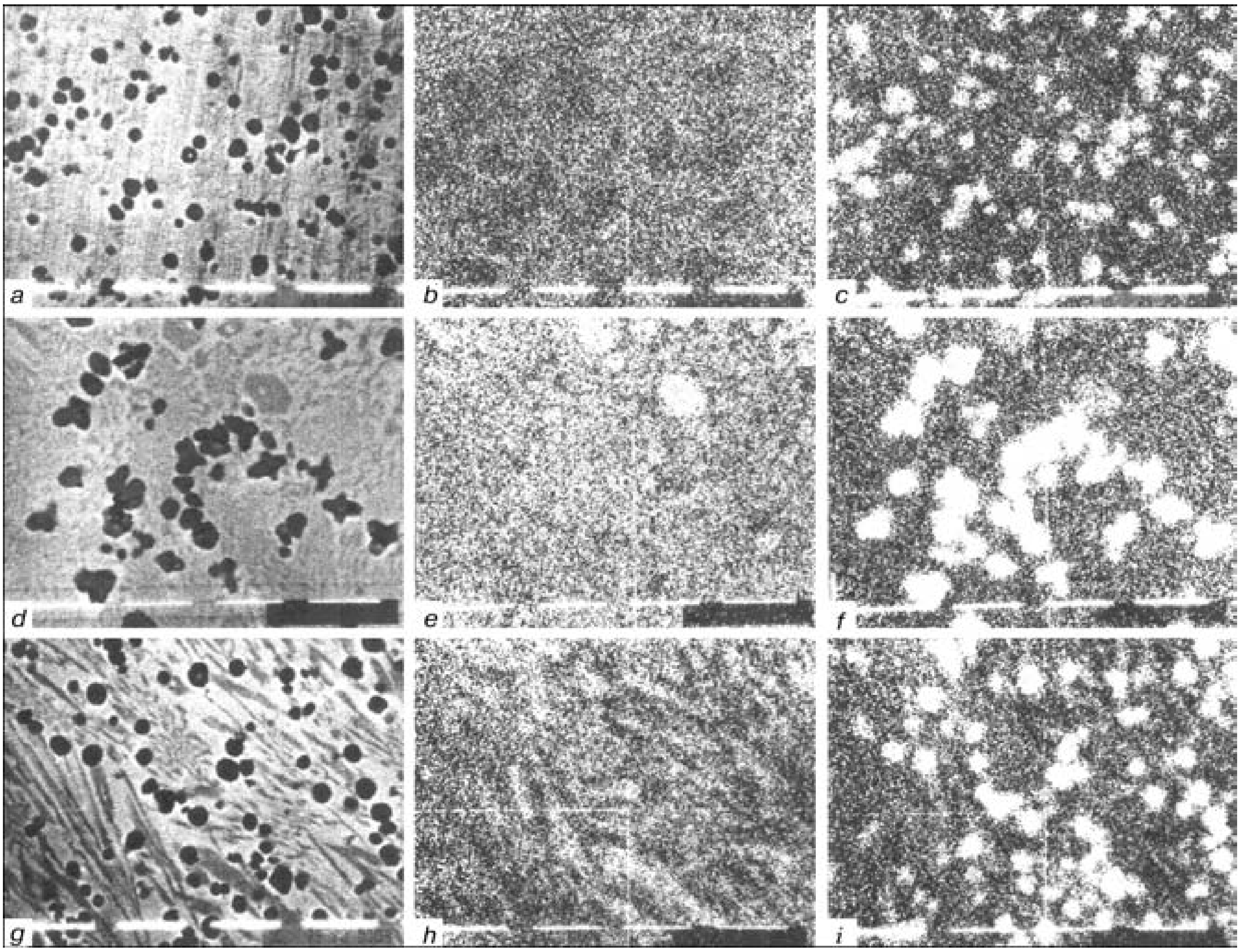

Figure 4. Distribution of alloying elements in high-carbon high-vanadium deposited metal as examined by electron scanning microscopy: *a, d, g* — in back-scattered electrons; *b, e, h* — scanning patterns of distribution of chromium; *c, f, i* — scanning patterns of distribution of vanadium; *a–c* — alloy No.2; *d–f* — alloy No.6; *g–i* — alloy No.5

that vanadium carbides of the VC type and chromium carbides of the $Me_{23}C_6$ type were uniformly distributed in structure of alloy No.5, and their size was no more than 10 μm (Figure 4, *d–f*). In alloy No.6 containing more carbon, coarse chromium carbides of the Me_7C_3 type (Figure 4, *g–i*) are formed, in addition to fine vanadium and niobium carbides of the MeC type, which can lead to spalling of the working edges of the knives. This factor makes this alloy more preferable for cladding of the knives with corrosion-resistant properties.

CONCLUSIONS

1. Optimal ranges of alloying of powders of alloys of the Fe–C–V–Cr–Mo system were determined for plasma-powder cladding of knives intended for cutting non-metallic materials. It is shown that for cladding of tools for cutting non-metallic materials having no corrosion-resistant properties, the most promising powder is that which has the following composition, wt.%: 4.0C, 14.0V, 6.0Cr, 1.5Mo. In cladding of knives with corrosion-resistant properties, the mass fraction of chromium should be increased to 14.0 %.

2. It was found that, depending upon the chemical composition of the high-carbon high-vanadium alloys, their structure may include martensite and austenite in different proportions, as well as a substantial amount of carbides of the main alloying elements, i.e. vanadium and chromium. The highest wear resistance under the abrasive wear conditions is provided by the martensitic structure with a small amount of retained austenite and dispersed, uniformly distributed vanadium carbides, as well as chromium carbides of the $Me_{23}C_6$ type.

1. Geller, Yu.A. (1975) *Tool steels*. Moscow: Metallurgiya.
2. Ryabtsev, I.A., Kondratiev, I.A. (1999) *Mechanised electric arc surfacing of metallurgical equipment parts*. Kyiv: Ekotekhnologiya.
3. Goudremont, E. (1966) *Special steels*. Vol. 2. Moscow: Metallurgiya.
4. Efimov, Yu.V., Baron, V.V., Savitsky, E.M. (1969) *Vanadium and its alloys*. Moscow: Nauka.
5. Livshits, L.S., Grinberg, N.A., Kurkumelli, E.G. (1969) *Principles of deposited metal alloying*. Moscow: Mashinostroenie.
6. Meskin, V.S. (1964) *Principles of steel alloying*. Moscow: Metallurgiya.
7. Pereplyotchikov, E.F., Gladky, P.V. (1973) Influence of plasma surfacing parameters on base metal penetration. In: *High-efficient surfacing processes and deposited materials*. Kommunarsk: KMK.
8. Gladky, P.V., Pereplyotchikov, E.F., Frumin, I.I. (1968) Plasma surfacing of chrome-nickel alloys with additions of silicon and boron. *Avtomatich. Svarka*, **9**, 58–62.
9. Ryabtsev, I.A., Kondratiev, I.A., Vasiliev, V.G. et al. (2002) Wear resistance of deposited metal of Fe–C–Cr–Ti–Mo alloying system. *The Paton Welding J.*, **4**, 45–48.
10. Palatnik, L.S., Papirov, I.I. (1964) *Directional solidification*. Moscow: Metallurgiya.

STRENGTH AND TOUGHNESS OF METAL OF WELDED JOINTS IN Al–Li ALLOYS

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The paper deals with the regularities of variation of the strength and toughness of welded joints in Al–Li alloys, depending on the composition of the base and filler materials, heat input in welding, structure and operating conditions.

Key words: *fusion welding, aluminum-lithium alloys, welded joints, structure, weld metal, fusion zone, HAZ, strength, fracture toughness, operating conditions, investigations, comparative analysis.*

The first Al–Li alloys were developed more than 70 years ago. Extensive research was required to optimize the composition, determine the temperature-time parameters of the technology of making the semi-finished products and their joints. This resulted in introduction of a series of Al–Li alloys, which are a new class of weldable high-strength structural alloys of two alloying systems — Al–Mg–Li (1420, 1421, 1423, 1424) and Al–Cu–Li (1450, 1451, 1460, 1461, 1463, 1464) — with ultimate strength of 400–420 and 500–550 MPa [1, 2].

Unique combinations of physico-mechanical properties of Al–Li alloys (high values of strength and modulus of elasticity at a small specific weight) make them very attractive, compared to the traditional high-strength aluminium alloys. A comparatively low rate of propagation of fatigue cracks in Li-bearing alloys, and high values of the coefficients of stress intensity, low-cycle fatigue strength, stress corrosion cracking resistance, layer and intercrystalline corrosion, allow considering these alloys in the class of the most promising structural materials for designing samples of advanced equipment with improved tactical and technical parameters.

The main difficulties of producing tight welds have already been overcome. These difficulties are related to manifestation of the metallurgical heredity of the semi-finished products of Al–Li alloys under the impact of the thermal cycle of welding. Original welding technologies have been developed, which provide a high quality of welded joints [3–6]. The strength of arc welded joints is up to 70–80 % of that of the base metal. Use of EBW provides a strength, close to that of the base metal. The extent of the HAZ in this case is essentially reduced, compared to joints, made by arc welding. Improvement of the metal properties is noted not only in the weld, but also in the weakest zone of the joints, namely on the boundary of fusion with the base metal [3].

Degree of base metal softening in welding of Al–Li alloys and HAZ extension are dependent, alongside the welding process, also on the alloy composition. Alloys, containing magnesium as the main alloying component, are less prone to loss of strength under the conditions of thermal impact of welding than Cu-bearing alloys. This is related to the fact, that magnesium addition greatly promotes acceleration of the processes of precipitation of strengthening δ'-phase (Al_3Li) and increase of its density in the metal, compared to addition of copper [1].

A disadvantage of Al–Li alloys is an increased brittleness of the metal, and, therefore, sensitivity to stress raisers, which, causing the intensificaton of the stressed state, establish the prerequisites for accelerated crack initiation in the metal, which is related to proneness of the Al–Li alloys to localization of deformation [1]. Results of testing samples of welded joints with different notch radii (from 0.25 to 0.10 mm) and a fatigue crack at off-centre tension showed (Figure 1), that increasing the sharpness of the stress raiser by 40–55 % reduces the value of the critical coefficient of stress intensity K_c, which determines the conditions for possible propagation of fracture. Range of scatter of its values varies, depending on the sharpness of the notch, simulating stress concentration in individual zones of the welded joint, and on the stress-strain condition of the structure, which is related to the temperature and duration of the thermal impact. In weld metal the scatter is 10 %, and in the fusion zone and HAZ 20–25 %, which is a significant distinctive feature of Al–Li alloys, compared to high-strength aluminium alloys AMg6 NPP (Al–Mg) and 1201 (Al–Cu).

A similar dependence is traceable also in evaluation of other characteristics of fracture resistance (Table). Values of crack tip opening displacement δ_c and energy of crack initiation (J-integral) are also different in the zones of the welded joint. The metal on the fusion boundary of the weld and the base metal has minimum values of δ_c and J-integral. Fracture toughness indices K_c and δ_c for this zone of welded joint are equal to 23 MPa$\sqrt{m}$ and 0.04 m, respectively. Values of J_c and specific work of crack propagation (SWCP) depend on the composition of alloys being welded. For 1421 alloy, containing magnesium, they are 3.1 and 4.5 J/cm^2, respectively. Use of copper as the alloying element, provides high values of J_c (4.0 J/cm^2) and SWCP (6.2 J/cm^2) in alloy 1460. The established regularities of variation of the pro-

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perties of Al–Li alloy joints are indicative of the influence of the condition of boundaries of weld crystallites and base metal grains in the zone of welding heating on the strength of adhesion between the matrix and the intermetallic phases, which determines the brittle fracture of the metal.

Different degree of impact of the sharpness of the mechanical notch and fatigue crack on K_c values in the zones of welded joints may be due to different quantity of Li-rich phases, precipitating in the areas of joining of the boundaries of weld crystallites in the weld metal and grains of base metal under the conditions of thermal impact of the welding process. Samples are particularly sensitive to the change of the sharpness of the notch tip in the case, if the latter coincides with the boundary of weld fusion with the base metal (Figure 1), which is related to the conditions and features of formation of the structure of this zone of the joint under the impact of the thermal cycle of welding. Increase of the density of precipitation of secondary phases as a result of decomposition of the solid solution, and coagulation of inclusions of insoluble intermetallic phases, proceeding under the conditions of welding heating, lead to formation of individual phase clusters or regions in the form of a dense framework along the grain boundaries. As the volume fraction of brittle regions increases, their level of stress concentration rises, thus increasing the yield point. This introduces the conditions for prefracture of the structure of welded joints of Al–Li alloys. The level of stressed state of the intergranular spacing is influenced not only by the dimensions and location of such regions, but also by the alloying elements of the alloy, included into the phase composition. According to the data, shown in Figure 1 and the Table, the metal of the boundary of fusion in joints of alloy 1460 is characterized by 1.5–2 higher indices of fracture resistance (K_c, δ_c and J-integral), compared to joints of alloy 1421. This is attributable to smaller diameter of copper atom (0.256 nm), included into the composition of alloy 1460, compared to the diameter of magnesium atom (0.32 nm), which is the main alloying element of alloy 1421 after lithium.

The probability of fracture of Al–Li alloy joints along the line of fusion with the base metal may be influenced also by the presence of slip lines in the semi-finished product being welded. Coarse clusters of disordered and disoriented fragments of the structure, formed by the slip lines along the rolling direction, are sites of plastic shear localizing, where intensive development of local stresses goes higher than the values of ultimate strength. This leads to weakening of adhesion forces of grain boundaries, and causes crack initiation due to particle fracture, both in the body and along the boundary of contact with the matrix. It should be noted, that initiation of an intergranular crack is due not to trivial macroscopic tear of one grain from another, but to running of a preliminary deformation, during which a critical structure forms in the near-boundary zone, in which

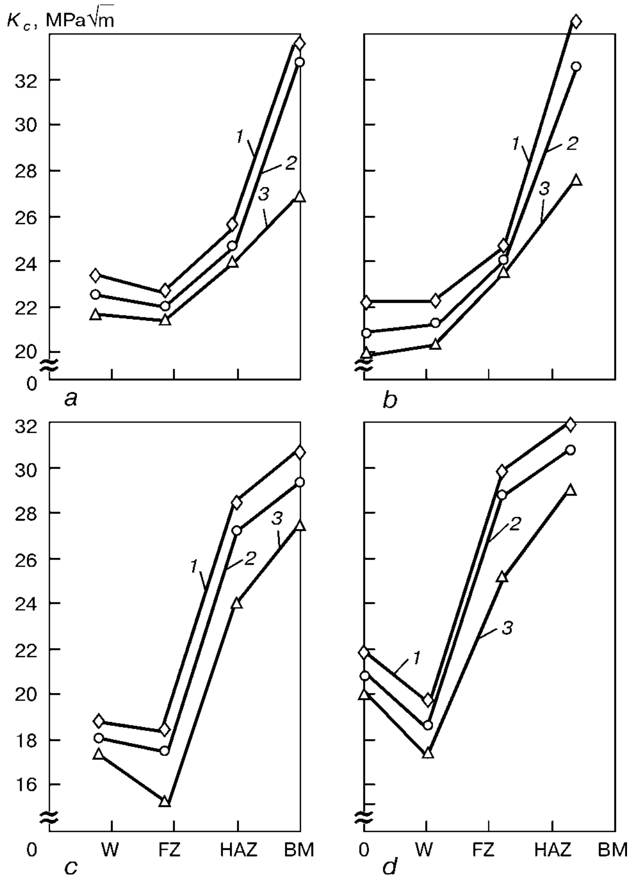

Figure 1. Influence of the sharpness of the notch R_n on values of critical coefficient of stress intensity in different zones of welded joints in high-strength aluminium alloys AMg6 NPP (*a*), 1201 (*b*), 1421 (*c*) and 1460 (*d*): *1* — R_n = 0.25; *2* — 0.10 mm; *3* — fatigue crack

numerous intergranular cracks arise and then coalesce (Figure 2). Presence of phase clusters on the boundaries enables manifestation on the macrolevel of the features of the process of relaxation of internal tensile stresses, developing in their intergranular space, under the conditions of the thermal cycle of welding.

Influence of a stress raiser becomes stronger under the conditions of the impact of embrittling factors, concurrent with service of a structure of Al–Li alloys

Influence of notch geometry on values δ_c and J-integral in Al–Li alloys 1421, 1460 and their welded joints

Alloy	*Studied zone*	δ_c, *mm*		*J-integral, J/cm²*
		V-shaped notch	*T-shaped notch*	
1421 (Al–Mg–Li)	BML	0.130	0.052	4.0
	BMT	0.110	0.045	3.0
	WM	0.183	0.087	5.8
	FZ	0.084	0.031	1.9
	HAZ (5 mm)	0.117	0.057	3.2
1460 (Al–Cu–Li)	BML	0.120	0.072	4.8
	BMT	0.119	0.060	3.1
	WM	0.183	0.104	6.0
	FZ	0.101	0.060	3.4
	HAZ (5 mm)	0.126	0.089	4.7

Note. Here BML and BMT is the base metal of longitudinal and transverse orientation relative to rolling direction; WM is the weld metal; FZ is the fusion zone metal.

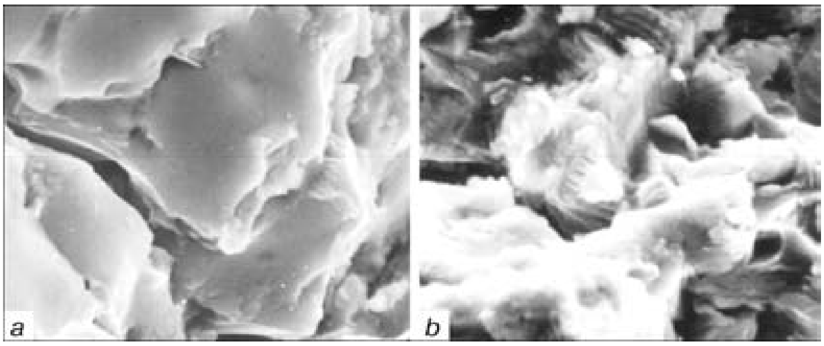

Figure 2. Surface of fracture of the metal on the boundary of fusion of arc-welded joints: *a* — 1421 alloy; *b* — 1460 alloy (×500)

(change of the loading pattern, deformation rate, working temperature). Investigation results [7, 8] showed that increase of deformation rate or lowering of testing temperature to 20 K leads to increase of the strength of welded joints of Al–Li alloys to 400–420 MPa due to strain or temperature hardening. Ductility of the joints either remains the same as at room temperature, or is lowered by 15–20 %, reaching the level of K_c and δ_c (23 MPa$\sqrt{m}$ and 0.04 mm, respectively). J_c and SWCP indices change, depending on the alloy composition. For Mg-containing alloys (1421) they are equal to 3.1 and 4.5 J/cm^2 and for alloys with copper (1460) — 4.0 and 6.2 J/cm^2, respectively. Higher values (by 30–40 %) of J_c and SWCP in alloys of Al–Cu–Li system confirm the rationality of applying them in structures, operating under the conditions of the impact of stress raisers and cryogenic environment.

At higher service temperatures (473 and 623 K), the strength of joints (320 MPa) decreases by 3–5 % and 3 times, respectively, compared to room temperature. Deformation and energy indices of fracture toughness change non-uniformly and depend on the dimensions and shape of brittle local sections, formed in the intergranular space at the thermal impact of the welding cycle. In the temperature range of testing from 300 up to 473 K, they rise by 10 % in the fusion zone metal and by 25 % in the weld metal [8]. Further increase of testing temperature up to 623 K reduces the strength and toughness 2 times, which is indicative of lowering of the local stress, required for initiation and development of a grain-boundary crack.

Increased proneness to embrittlement of joints in Al–Li alloys, compared to basic alloys, is attributable to the presence of excess phases in the intergranular space, due to a high degree of their alloying, which prevents stress relaxation during deformation. Accumulated stresses lead to development of an unfavourable coplanar type of dislocation structure, which is revealed after sample breaking up in testing [1, 2, 9]. Brittle fracture in this case results from occurrence of even though intensive, but highly localized plastic flow, which is possible at a very low level of shear stresses, and which simultaneously leads to development of large and hazardous dislocation clusters, which creates prerequisites for crack initiation. Such a feature of the alloys is related to lithium susceptibility to plane sliding during its redistribution along grain boundaries, which results in ductility lowering.

Decrease of lithium content in the alloy (to 1.7–1.9 at.%) provides a 1.5 times increase of relative elongation [10]. Positive influence on physico-mechanical properties of Al–Li alloys is also noted, when using modes of two-step annealing with intermediate deformation up to 3 %, which is attributable to formation of a favourable structure of the alloys [11]. Straightening, performed after quenching, inhibits formation of the brittle phase, speeds up dissolution of strengthening δ'-phase (Al_3Li) and somewhat reduces its dimensions, which has a favourable impact on K_c.

Increase of relative elongation by 7 % is noted also at addition of such a modifier as scandium to the alloy composition [1]. Experimental evaluation of the characteristics of fracture resistance of welded joints in Al–Li alloys 1420 and 1421, depending on the amount of scandium in the base and filler materials of alloys of Al–Mg or Al–Cu system showed that the weld metal is characterized by 20 % higher strength at 0.4–0.6 % Sc in the wire [12–14]. In this case formation of a fine-crystalline and subgrain structure results in SWCP being equal to 8–10 J/cm^2, due to a complete dimensional-structural similarity between the disperse particles of scandium aluminide and the matrix: σ_{br} = 310–320 MPa, K_c = 25–28 MPa$\sqrt{m}$, δ_c = = 0.05–0.07 mm, J_c = 4–6 J/cm^2. Favourable influence of the produced microstructure on the toughness consists in that the crack propagation is retarded by effective barriers (grain boundaries), and more energy is spent for finding a new direction of its propagation than in the case of a coarse grain. Moreover, presence of scandium in the base metal, promotes retardation of recrystallization processes, which proceed in welding of aluminium alloys, thus reducing the extent of the softening zone [3]. The above effect is highly important, as it allows lowering the requirements, when specifying the temperature-time conditions in welding of Al–Li alloys.

However, overheating of Al–Li alloys in welding has a pronounced influence on the processes of crack initiation in them, and determines the fracture mode [15]. Greater time of the metal staying under the conditions of high temperatures (673–773 K) in the welding process promotes formation of more extended clusters of brittle components of the structure (oversaturated and intermetallic phases), which hinder the plastic shear in deformation. Their appearance is due to intensive development of structural inhomogeneity because of different content of alloying elements and impurities near the grain boundaries at segregation. An increase of stress concentration is found with the increase of volume fraction of such regions in the structure of welded joints, which is indicated by formation of flat sections of the relief along the boundaries of crystallites and grains in fractures of broken samples. Indices of strength and fracture toughness of welded joints, compared to those of base metal, are lower in this case: σ_{br} = 265 MPa, K_c = = 21.5 MPa$\sqrt{m}$, δ_c = 0.03 mm, J_c = 2.5 J/cm^2; SWCP is equal to 3.8 J/cm^2.

Extent of regions of an unfavourable structure is reduced 4–10 times, when welding processes and modes are used, which are characterized by minimal heat input, for instance pulsed arc (10–13)$\cdot 10^5$ J/m or electron beam (1.2–1.4)$\cdot 10^5$ J/m. In this case, formation of brittle intercrystalline (in welds), intergranular (in HAZ) interlayers and microcavities is prevented in the fusion zone, which lowers the probability of crack initiation and improves the properties of welded joints. Nominal breaking stress σ_{br} in individual zones of the joints in this case increases by 70–100 MPa, and K_c by 20–25 % [15]. Improvement of physico-mechanical properties is achieved not only in the weld metal, but also in the weakest zone of welded joints, namely on the boundary of fusion with base metal, which may guarantee reliable performance of welded joints in structures of Al–Li alloys.

Lowering of stress concentration along the boundaries of crystallites and grains can be achieved by reducing the content of phase inclusions, for instance, intermetallic, which have a higher brittleness. Their composition and amount are determined by alkali and alkali-earth elements (sodium, calcium, barium, potassium), penetrating into Al–Li alloys at the metallurgical stage of manufacturing. Degree of alloy embrittlement depends both on the initial arrangement and on the form of the phases, containing these impurities [1], even thousand fractions of a percent of which have an adverse influence on the properties of alloys and welded joints, because of lowering of the melting temperature of phases, precipitating along grain boundaries. This makes them highly prone to fracture propagation. Accumulation of atoms of alkali and alkali-earth elements along the boundaries of crystals and grains of base metal, resulting from their high chemical affinity to aluminium, increases the degree of embrittlement of Li-bearing alloys, and causes grain-boundary cracking. With 0.10–0.15 % of inclusions, no deterioration of strength properties is found, and the ductility and fracture toughness indices decrease by 30–40 % [16, 17]. Susceptibility of Li-bearing alloys to embrittlement, resulting in cracking, is less pronounced at decrease of impurities to 0.01 %. This provides a 20 % increase of nominal breaking stress σ_{br} and 40 % increase of K_c. Values of other indices of fracture resistance with uniform distribution of intermetallics are as follows: δ_c = = 0.05 mm, J_c = 4 J/cm^2; SWCP is equal to 5.2 J/cm^2. Intercrystalline mechanism of fracture in the fusion zone in this case changes to transcrystalline.

Thus, improvement of structural conditions of the boundaries of crystallites and grains allows really controlling the strength and toughness of welded joints in Al–Li alloys of 1421 and 1460 type. Limiting the heat input (specific energy) by using pulsed modes of arc welding or EBW allows eliminating formation of brittle regions with unfavourable structure and providing satisfactory characteristics of strength and fracture toughness of items of aerospace systems in extreme conditions of operation in a broad temperature range (20–500 K). Effectiveness of the technologies is confirmed by the results of their production trials and introduction into pilot production of welded structures of load-carrying shells of aircraft and helicopters, as well as fuel tanks for reusable space vehicles [5, 18–20].

1. Fridlyander, I.N., Chuistov, K.V., Berezina, F.L. et al. (1992) *Aluminium-lithium alloys, structure and properties*. Kyiv: Naukova Dumka.
2. Fridlyander, I.N., Beletsky, V.M., Krivov, G.A. (2000) Aluminium alloys in aircraft structures. *Tekhnolog. Sistemy*, **1**, 5–17.
3. (1998) *Welding in aircraft construction*. Ed. by B.E. Paton. Kyiv: MIIVTs.
4. Ishchenko, A.Ya., Labur, T.M., Lozovskaya, A.V. (1995) Aluminium-lithium alloys for aerospace engineering welded structures. *Avtomatich. Svarka*, **2**, 41–44.
5. Ovchinnikov, V.V., Drits, A.M., Krymova, T.V. (1997) Technological peculiarities of manufacturing of aircraft welded structures from aluminium-lithium alloy 1460. *Svarochn. Proizvodstvo*, **12**, 26–29.
6. Ilyushenko, R.V., Lozovskaya, A.V., Sklabinskaya, I.E. et al. (1991) Structure and properties of aluminium-magnesium-lithium alloy welded joints. *Avtomatich. Svarka*, **7**, 23–26.
7. Labur, T.M. (1996) Properties of aluminium alloy welded joints under low-temperature conditions. *Ibid.*, **11**, 30–32, 36.
8. Labur, T.M. (1994) Change of fracture resistance of welded joints of 01421 alloy under high-temperature heating conditions. *Ibid.*, **12**, 8–11.
9. Hertsberg, R.V. (1989) *Deformation and fracture mechanics of structural materials*. Moscow: Metallurgiya.
10. Kojima, Y. (1989) Aluminum-lithium alloys. *Welding Light Metal*, **1**, 67–80.
11. Elagin, V.I., Orozov, A.I., Shcheglova, N.M. et al. (1996) Investigation of the influence of normalizing thermo-mechanical treatment on properties of 1571, 1430, 1441 alloy sheets. *Tekhnologiya Lyog. Splavov*, **5**, 40–43.
12. Labur, T.M., Ilyushenko, R.V. (1992) Influence of scandium additives in filler wire during welding of 1420 aluminium alloy. *Avtomatich. Svarka*, **11/12**, 53–54.
13. Labur, T.M., Ilyushenko, R.V. (1993) Influence of scandium on fracture resistance characteristics of welded joints of 1420 and 1421 alloys. *Tekhnologiya Lyog. Splavov*, **12**, 37–41.
14. Labur, T.M. (1996) Investigation of the efficiency of weld metal strengthening by scandium in welding of aluminium-lithium alloy 1420. *Avtomatich. Svarka*, **7**, 17–19.
15. Labur, T.M., Bondarev, Andr. A., Lozovskaya, A.V. et al. (2001) Influence of welding process on fracture resistance of joints in aluminium-lithium alloys 1420 and 1460. *The Paton Welding J.*, **7**, 11–15.
16. Grushko, O.E., Sheveleva, L.M. (1994) Additives of alkali and alkali-earth metals in aluminium-lithium alloy 1420. *Tsvetnye Metally*, **4**, 48–51.
17. Labur, T.M. (1998) Influence of addition elements on fracture resistance. *Avtomatich. Svarka*, **6**, 40–43.
18. Imamura, T. (1991) Application of light metals in structures of flying vehicles. *Keikinzoku*, **9**, 623–634.
19. Birk, R.K., Dajkus, D.P., Fridlyander, I.N. et al. (2001) Aluminium-lithium alloy 1441 as an advanced material for fuselage. *Metallovedenie i Term. Obrab. Metallov*, **8**, 7–10.
20. Barabokhin, N.S., Bushuev, Yu.G., Shulgina, E.V. et al. (1999) Technological peculiarities of welding high-strength aluminium alloy 1460. *Svarochn. Proizvodstvo*, **11**, 12–14.

EFFECT OF PARAMETERS OF HEATING THE SURFACE OF A PART ON STRUCTURE OF HARDENED LAYERS OF STEEL U8 IN PLASMA-DETONATION TREATMENT

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Temperature fields of surface layers during the process of plasma-detonation treatment of parts were determined on the basis of solving the non-stationary equation of thermal conductivity by the finite difference method. The resulting calculation dependencies were used to analyse kinetics of phase transformations in structure of steel U8 during PDT.

Key words: *plasma-detonation treatment, carbon steels, absorbing coatings, process parameters, metallography, X-ray phase analysis*

Repair of wearing surfaces of various tools and machine parts made from low-alloy and carbon steels is often the most cost-effective way of extending their service life. In this connection, very topical are the studies aimed at development of new repair and, at the same time, hardening technologies that use concentrated energy sources, such as laser, electron and ion beams and plasma.

The use of the latter generated by pulse plasma accelerators at discharge of capacitor banks is one of the most promising methods for surface treatment. One of them is plasma-detonation treatment (PDT) [1, 2]. Energy parameters of the flow achieved in this case are similar to parameters achieved in the case of using a laser heat source ($1\cdot10^8$–$5\cdot10^{10}$ W/m^2). Nevertheless, there are some differences in the mechanism of surface heating between the laser effect and PDT. While interacting with an absorbing environment, the laser beam is partially reflected from the surface and partially penetrates deep into a material. Absorbing coatings (e.g. colloidal solution of graphite deposited on an exposed surface in the form of film not more than 50 μm thick) are used in laser treatment to increase the absorbing ability of the surface. It is a known fact that the absorbing ability of a material increases with decrease in its electrical conductivity [3]. Therefore, the efficiency of laser treatment grows in the case of using non-metallic coatings (Fe_2S_3, Al_2O_3, $Mn_3(PO_4)_2$, $Zn_3(PO_4)_2$).

Character of interaction of a plasma jet with the surface in PDT depends upon the velocity of the jet, shape and size of the surface, as well as location of the latter with respect to the plasmatron nozzle. If surface of a workpiece is located in a region before the first shock wave (supersonic flow region), a shock-compressed plasma region substantially differing in its light and physical characteristics from the rest of the flow region is formed ahead of it. Thickness of the shock region depends upon the velocity of the jet, while for a preset velocity it is maximum if the jet affects a flat barrier [4]. The shock-compressed plasma results in heat transfer into a workpiece. A characteristic feature of PDT is the possibility of connecting the workpiece to the discharge circuit (its grounding). Investigation of amplitude-time characteristics of the current in PDT is described in [5]. Heating of the surface layer of a material occurs due to a heat flow into the workpiece, the heat flow consisting of the energy transferred by electrons, ions, neutral atoms, radiant component and volumetric Joule heat release during the process of passage of the pulsed current. Value of each of the components depends upon the plasma jet parameters and surface condition, as well as upon the presence or absence of potential at the workpiece. If the workpiece is connected to the discharge circuit, polarity becomes important, as PDT makes it possible to realise the processes of alloying of the surface layers, in addition to heat treatment. Similar to spark-discharge alloying [6], PDT is most effective if the consumable electrode serves as the anode and the workpiece serves as the cathode.

Purpose of this article is to reveal the effect of some factors of surface heating in PDT on structure of the hardened layers of steel U8, and evaluate the role of a radiant component in PDT and importance of connecting a workpiece to the discharge circuit in particular.

Materials and investigation methods. Investigations were conducted on samples made in the form of cylinders 5 mm high and 20 mm in diameter from eutectoid steel U8 (wt.%: 0.74–0.85C; up to 0.2Cr; 0.15–0.35Si; 0.2–0.4Mn). Preliminarily, the samples were subjected to volumetric water quenching from 820 °C and subsequent tempering at a temperature of 200 °C for 40 min. Microhardness of surface layers of the samples after heat treatment was *HV* 4500–5000 MPa. Materials applied in practice of laser treatment (Table 1) were used to study the effect of a coating material in PDT in terms of enhancing a radiant heat transfer. PDT was performed by using the «Impulse» machine under the following process conditions: voltage at the capacitor bank plates — 3.2 kV, inductance of the discharge circuit — 20 μH, pulse frequency — 2 Hz, flow rate of propane C_3H_8 —

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Table 1. Materials of absorbing coatings and their characteristics

Coating material	*Thickness, μm*	*Electrical conductivity*	*Absorption coefficient [3, 7]*
Carbon black	< 5	Conductor	0.4–0.8
Printing ink	30–40	Same	< 0.96
$Zn_3(PO_4)_2$	6–10	Insulator	0.55–0.90

0.35 m^3/h, flow rate of oxygen — 1.4 m^3/h, flow rate of air — 1.3 m^3/h, capacitance of the capacitor bank — 800 μF, distance from the nozzle exit section to a workpiece — 40 mm, distance from the central electrode tip to the nozzle exit section — 20 mm, and consumable electrode material — molybdenum. State of the surface and variable process parameters for treatment of the samples are given in Table 2.

Structural-phase analysis of a layer formed as a result of PDT was carried out by the metallography and X-ray phase methods using the «Neophot 32» optical microscope and DRON-3 diffractometer with a cobalt source of K_α-radiation. The depth of penetration of X-rays was 10–15 μm. Investigation of a general character of distribution of chemical elements on the surface within the zone affected by plasma detonation was conducted using the JEOL scanning electron microscope JSM-840. To reveal microstructure of the surface layers, the sections were subjected to electrolytic etching in a 10 % chromium anhydride solution. Hardening of the surface layer was characterised by microhardness measured on metallographic sections. Measurements were conducted using the LECO hardness meter M-400 with a load of 50 g. The degree of tetragonality of martensite was determined from doublet spacings of lines of the α-phase [8]. The method of homological pairs was employed to determine the amount of retained austenite [9].

Table 2. Surface state and variable process parameters for treatment of samples

Sample No.	*Presence of potential*	*Surface state*	*Coating composition*	*Number of pulses*
1		Untreated		
2	Insulated	Polished	–	1
3	Same	Coated	Carbon black	1
4	Grounded	Polished	–	1
5	Same	Coated	Carbon black	1
6	»	Polished	–	3
7	»	Coated	Carbon black	3
8	»	Same	$Zn_3(PO_4)_2$	1
9	»	»	Same	3
10	»	»	Printing ink	1
11	»	»	Same	3

Results and discussion. Connection of a sample to the discharge circuit (sample No.6, Figure 1, *a*) results in formation of a clearly defined zone of localisation of the current channel with a diameter of about 6–8 mm. Connection of the sample to the discharge circuit and presence of a carbon black coating (sample No.7, Figure 1, *b*) result in formation of heat-affected zones in the peripheral zone, which is indicative of a decrease in contraction of the pulsating arc at the workpiece surface. Disconnection of a workpiece from the discharge circuit (samples No.2 and 3), as proved by metallography, leads to a marked decrease in heat flows to the region treated. Here, as a result of an ambipolar diffusion of particles from the bulk of plasma, the surface has a floating negative potential with respect to potential of the adjoining plasma layer [10]. Difference of potentials is $\Delta\varphi = 4–6$ V. This results in a substantial decrease in heating of the surface due to reduction of part of the heat flow associated with the energy transferred by elec-

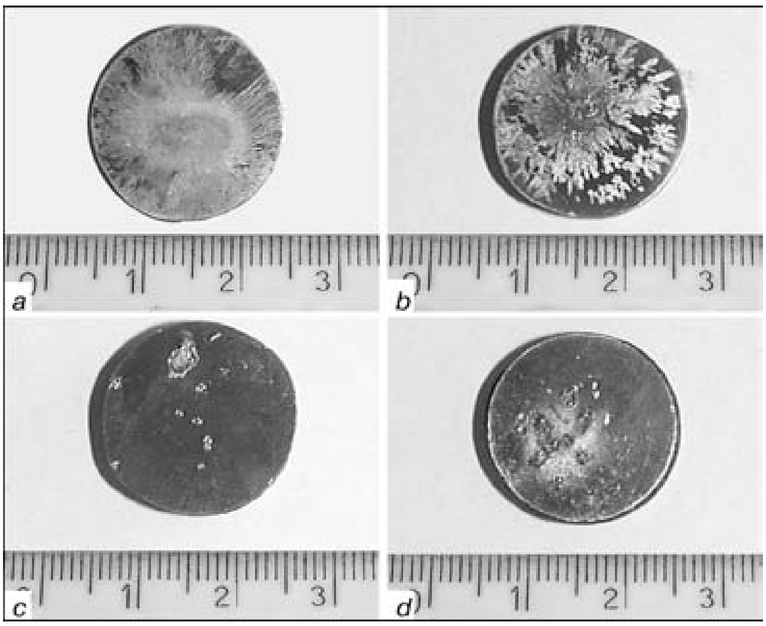

Figure 1. Appearance of samples No.6 (*a*), 7 (*b*), 10 (*c*) and 11 (*d*) after PDT (treatment parameters are given in Table 2)

trons, as well as to the absence of a volumetric Joule heat release. Phosphate coatings, having low electrical conductivity, insulate the surface from the electric current, whereas increase in the radiant component does not compensate for the heat flow losses. Decrease in heat flows in the case of using phosphate coatings is caused by the same factors as in the case of disconnecting the workpiece from the discharge circuit. The use of a printing ink (samples No.10 and 11, Figure 1, *c, d*) as coatings leads to formation of craters on the sample surfaces. They are formed in locations where the coating is the thinnest and, thus, the ohmic resistance is the lowest. Current density in these regions is high.

Therefore, the use of a material with low electrical conductivity (zinc phosphate) as coatings absorbing the radiant energy, as well as C-base coatings (printing ink) of a large thickness (> 30 μm) does not as a total lead to increase in heating of the surface layer of a material treated. In terms of increasing the radiant component of the heat flow under the PDT conditions, the best coatings are coatings of carbon black, having high electrical conductivity and promoting formation of a medium with an increased carbon content on the workpiece surface.

Like after other methods of surface hardening using concentrated heat sources, etching of the surface subjected to PDT reveals a slightly etched white layer on this surface (Figure 2). The presence of this layer was not revealed on the microsections, where the samples were treated with no application of electric potential. This is indicative of the fact that in this case the energy density in the treated spot is below $2\cdot10^8$ W/m^2 [11]. Connecting this spot treated by one pulse (samples No.4 and 5) to the discharge circuit results in formation of a layer with a non-uniform thickness. It is hardly noticeable in some places of the treatment zone, while in the other places its thickness amounts to 40 μm (Figure 2, *a, b*). Microhardness of the white layer is about 6500–8000 and that of the substrate is 4500–5000 MPa. After the three-fold treatment the layer becomes more uniform over the entire heat-affected region (Figure 2, *c, d*), its thickness amounts to 40 μm and microhardness — to 8600 MPa. Scanning electron microscopy also revealed deposition of a material of the eroded anode-electrode (Mo) on the surface. These data evidence that deposition of the vapour-drop phase of the electrode material enables the alloying processes to be performed during PDT.

As seen from the X-ray pattern (Figure 3) of tempered steel without PDT (sample No.1), the process of tempering of a quenching structure resulted in precipitation of carbon from martensite and considerable decomposition of austenite. Therefore, the phase composition of steel prior to PDT consists of a tempered low-carbon (≈ 0.13 % C) martensite with a lattice close to a cubic one. In addition, the X-ray pattern shows peaks of Fe_3C, i.e. cementite, weak peaks of retained austenite and low-temperature ε-Fe_3C carbide. The X-ray pattern of sample No.2 is similar to that of sample No.1. Peaks of α-Fe and Fe_3C are fixed. This proves an insignificant heat effect on the surface with insulation of a workpiece. In addition, there

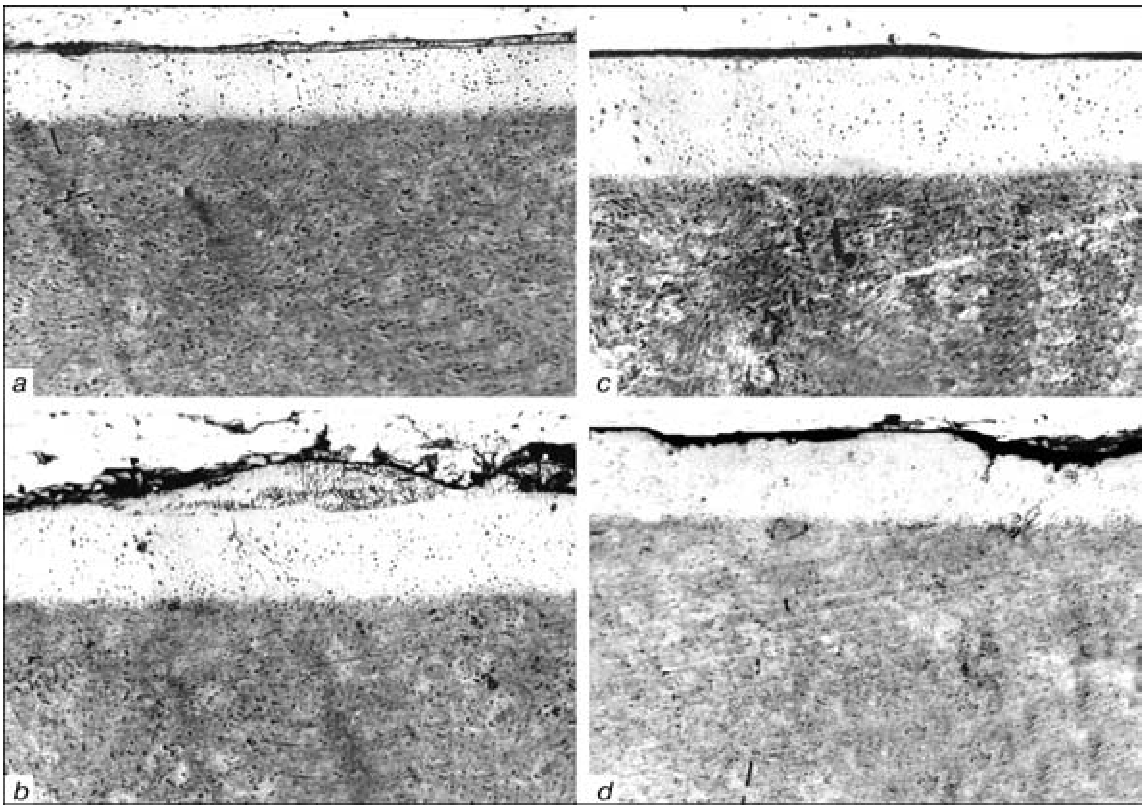

Figure 2. Microstructure of samples No.4, 5 (*a, b*), 6 and 7 (*c, d*) (steel U8) after PDT. Electrolytic etching in 10 % chromium anhydride solution: *a, b, d* — ×500, *c* — ×800

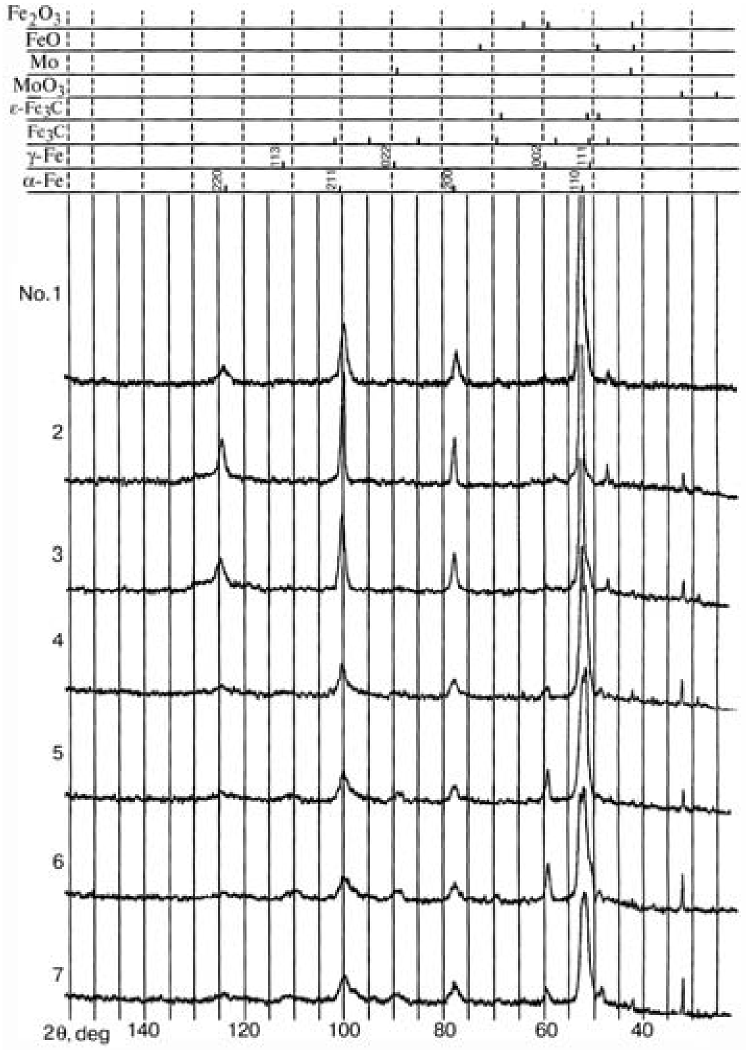

Figure 3. X-ray patterns of surfaces of an initial sample and samples after PDT (treatment parameters are given in Table 2)

appeared a pronounced peak corresponding to MoO_3, as well as weak peaks of molybdenum, which is indicative of transfer of electrode material to the workpiece surface. The use of carbon black as the coating to increase the emissivity factor of the surface does not lead to a marked change in type of the X-ray pattern. The X-ray pattern of sample No.3 is identical to that of sample No.2. Connecting the sample to the discharge circuit, other treatment conditions being equal, leads to a considerable change in the type of the X-ray pattern of sample No.4, which shows a substantial decrease in the intensity of the α-Fe lines and formation of the retained austenite lines. The α-Fe line (110) is split into a pair of the martensite lines (110) and [(011) (101)] located closely to each other. Tetragonality of the lattice is increased because of saturation of martensite with carbon. Widening of the doublet spacing is seen at peaks (200) and (211), which proves increase in tetragonality of the martensite lattice. Increase in the carbon content of martensite is caused, firstly, by dissociation of the carbide phases (the Fe_3C and α-Fe_3C peaks almost disappeared from the X-ray patterns), and, secondly, the possibility exists of carbon saturation from the plasma environment. The treatment was performed in a reduction atmosphere with an excessive content of C_3H_8. The X-ray pattern now shows the peak of wustite FeO. Carbide MoC also might exist. It is very difficult to detect its presence because of close values of the inter-plane distances in the crystalline lattices of MoC and FeO. The presence of an absorbing coating in the form of carbon black on the workpiece surface (sample No.5) leads to decrease in the content of oxides. Besides, increase in the heat effect due to a radiant flow is noted. This leads to a growth of the

Table 3. Carbon content of martensite and retained austenite content of surface layers of steel U8 after PDT (treatment parameters are given in Table 1)

Sample No.	*Carbon content of martensite, %*	*Austenite content, %*
1	0.13	< 5
2	0.13	< 5
3	0.13	< 5
4	0.44	13
5	0.54	21
6	0.64	30
7	0.68	18

austenite content (peak (002) of γ-Fe, sample No.5, Figure 3). The doublet spacing of γ-Fe (002)–[(020) (200)] in the X-ray pattern of sample No.5 is larger than that of sample No.4, which is indicative of increase in tetragonality of martensite. Increase in the number of pulses to three (sample No.6, Figure 3) promotes further growth of a relative intensity of the retained austenite peaks. The intensity of the MoO_3 peak grows to a substantial degree. The maximum carbon content of martensite was fixed in the X-ray pattern of sample No.7. The γ-Fe line (112) is split into a pair of the high-carbon martensite lines (112) and [(121) (211)].

Smearing of lines in X-ray patterns of the samples after PDT is indicative of a stressed state of the treated surface as a result of phase hardening, which makes identification of the X-ray patterns a bit more difficult. Widening of the X-ray lines is larger under a more intensive energy effect on the surface, which was fixed in X-ray patterns of samples No.6 and 7. Despite a rather high austenite content, hardness in the surface layers increases due to phase hardening as a result of reversible α-γ transformations. Table 3 gives results of estimation of the carbon content of martensite and the retained austenite content of the surface layers of samples of steel U8 after different types of PDT.

It is a known fact that if martensite contains 0.7 % C, hardness amounts to a maximum value of *HRC* 64, and with further increase in the carbon content it does not markedly increase [12]. Growth of the carbon content of martensite with increase in the number of pulses is associated with saturation of the workpiece surface with carbon from the plasma environment. The maximum carbon content of martensite was fixed in sample No.7. This is associated with the fact that in addition to saturation of the surface with carbon from the plasma environment, part of it diffuses into the surface layers during PDT directly from the preliminarily applied coating (carbon black). The amount of retained austenite grows with increase in the number of plasma pulses. After PDT its content of the surface layer may amount to 30 %, which is much higher than after furnace hardening. This is attributable to a higher heating temperature during PDT, as well as to a higher cooling rate preventing the austenite decomposition process. Similar results were obtained in surface treatment using other concentrated heat sources [13, 14].

CONCLUSIONS

1. Deposition of absorbing coatings on a surface treated has an ambiguous effect on the process of PDT of parts. The positive effect was fixed in the case of using thin (< 5 μm) C-base coatings, e.g. carbon black. This results in an insignificant intensification of the heat flow due to its radiant component, as well as increase in tetragonality of martensite due to diffusion of carbon into the surface layers.

2. Thick (≈ 40 μm) coatings based on printing ink and coatings of zinc phosphate (≈ 8 μm) with a high electrical resistance act as barriers for the flow of energy transferred by electrons, neutral atoms and ions. Increase in the radiant component does not compensate for these losses, which leads to a general decrease in the intensity of surface heating.

3. In PDT of an insulated workpiece, its surface is at a negative floating potential with respect to potential of the adjoining plasma layer. This leads to a marked decrease in the heat flow transferred by the electron component and to elimination of the volumetric Joule heat release, thus resulting in decrease in the energy density in the treatment spot below the level required for efficient modifying of the surface structure.

4. The investigations proved that PDT enables alloying of the surface due to transfer of the eroded electrode material. For efficient realisation of this process PDT should be conducted in a mode where the eroded electrode serves as the anode with respect to the workpiece surface.

1. Borisov, Yu.S., Tyurin, Yu.N. (1991) *Hardening treatment of machine parts by high-energy plasma*. Kyiv: PWI.
2. Tyurin, Yu.N., Kolisnichenko, O.V., Tsygankov, N.G. (2001) Pulse-plasma hardening of tools. *The Paton Welding J.*, **1**, 38–44.
3. Kovalenko, V.S., Golovko, L.F., Chernenko, V.S. (1990) *Laser hardening and alloying of machine parts*. Kyiv: Tekhnika.
4. Kisilevsky, L.I., Morozov, V.A., Snopko, V.N. (1974) Properties and application of pulsed high-enthalpy supersonic plasma jets. In: *Physics and application of plasma accelerators*. Ed. by A.I. Morozov. Minsk: Nauka i Tekhnika.
5. Borisov, Yu.S., Kolisnichenko, O.V. (2000) Investigation of amplitude-time characteristics of the current pulse in plasma-detonation treatment of items. *The Paton Welding J.*, **12**, 55–59.
6. Samsonov, G.V., Verkhoturov, A.D., Bovkun, G.A. et al. (1976) *Electric spark alloying of surfaces*. Kyiv: Naukova Dumka.
7. Soloviov, V.A. (1988) Determination of absorption factor of coating-metal system in CO_2-laser radiation conditions. *Fizika i Khimiya Obrab. Materialov*, **3**, 102–106.
8. Mirkin, L.I. (1979) *X-ray examination of engineering materials*. Refer. Book. Moscow: Mashinostroenie.
9. Bekrenev, A.N., Konstantinov, M.P. (1995) X-ray determination of residual austenite content of steels. *Zavodskaya Laboratoriya*, **2**, 42–43.
10. Rajzer, Yu.P. (1992) *Physics of gas discharge*. Moscow: Nauka.
11. (1985) *Reference book on laser treatment technology*. Ed. by V.S. Kovalenko. Kyiv: Tekhnika.
12. Gulyaev, A.P. (1986) *Physical metallurgy.* Manual for higher education establishments. 6th ed. Moscow: Metallurgiya.
13. Gureev, D.M. (1994) Laser effect on carbon redistribution in surface layers of tool steels. *Fizika i Khimiya Obrab. Materialov*, **1**, 27–39.
14. Voloshin, M.N., Gasin, D.A., Korablyova, I.R. et al. (1994) Peculiarities of U8 steel hardening using pulse-plasma treatment. *Ibid.*, **1**, 16–20.

DETERMINATION OF ADMISSIBLE DEVIATIONS OF INSERTS IN REPLACEMENT OF AN ASSEMBLY JOINT IN THE WALL OF COILED TANKS

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The paper deals with restoration of the serviceability of vertical assembly joints of the wall of coiled tanks by successive cutting out of the sections of aligned welds and welding rectangular inserts into the girths. It is shown that insert deviation from the design position induces additional local stresses along the vertical line of transition from the insert to the shell, as well as in the insert center, which requires establishing certain deviation tolerances. A criterion is suggested to determine the tolerances for deviation of rectangular inserts from the design position.

Key words: *coiled tanks, vertical walls, assembly joints, geometrical shape, welding-in of inserts, admissible deviations*

Restoration of serviceability of aligned vertical assembly joints now is an urgent problem, arising in repair of cylindrical steel tanks, which were constructed by the coiling method [1, 2]. One of the methods to solve the problem, proposed at the PWI, is replacement of aligned assembly joints by joints with shifting of the welds in the girths. The existing joint is cut out section by section, and special inserts are welded instead of it (Figure 1) with welds shifting, equal to not less than 15 thicknesses of the girth [3].

After the inserts have been welded into the tank wall, their geometrical shape will differ from the design shape, due to the influence of various factors (variation of the dimensions of transverse shrinkage, accuracy of assembly, etc.). It is established [4] that the existing criteria of evaluation of local deviations from the geometrical shape of the tank wall [3] by the gap between the wall and 1 m long gauge, are not always applicable for inserts. On the other hand, presence of such deviations causes considerable additional bending stresses. In order to limit these stresses, it is necessary to determine additional tolerance for deviations of the geometrical shape of inserts from the design shape, proceeding from local strength concepts.

At the first stage of development of tolerances for dimensions of depressions in the tank wall [5], included into the code [6], the main attention was given to prevention of «collapsing», which may lead to the wall breaking up.

Later, in addition to that, also the influence of depressions on the stressed state of the wall began to be evaluated. The depression in this case was considered as a spherical symmetrical shell [7], or a local corrugation in a ring of unit height. The finite element method was also used, allowing description of the actual shape of the depressions and evaluation of their influence on the stressed state of the wall [8].

Available published data on the stressed state of the cylindrical shell of the tank wall with a rectangular depression are insufficient to determine the admissible deviation of the geometrical shape of inserts. The stressed state of the tank wall with a rectangular-shaped depression was investigated, in order to determine the additional tolerances for the above deviation.

Considering, that the depression and the shell are described by different shapes of the surface, determinant relationships of the theory of shells were defined in the common curvilinear system of co-ordinates [9].

The process of deformation of thin shells within the finite deformations was studied, using the Lagrangian approach. Discretization of the resolving system of scalar differentials in calculation of the stressed state of depressions was performed with the method of curved grids [10]. The problem was solved in the non-linear definition, using the MEKRIS-2 program system [11].

The cylindrical shell was represented by its median surface in the parametric form

$$x = r \sin x^1; \quad y = r \cos x^1; \quad z = x^2, \tag{1}$$

where r is the radius of cylindrical shell, which in the area of the depression is described by the following equation:

$$r = r_0 + a_0 \cos \frac{\pi x^1}{\alpha} \cos \frac{\pi x^2}{l}, \tag{2}$$

where r_0 is the design radius; a_0 is the depth of depression; α is the central angle of the depression arc; l is the length of depression arc.

A simplified calculation schematic of an imperfect shell of a tank wall with a depression of a rectangular shape of depth $a_0 = -20$ was considered. 1/4 of the zone, surrounding the depression (Figure 2), was singled out from an infinite cylindrical shell of 10 mm thickness and 19950 mm radius (corresponding to a

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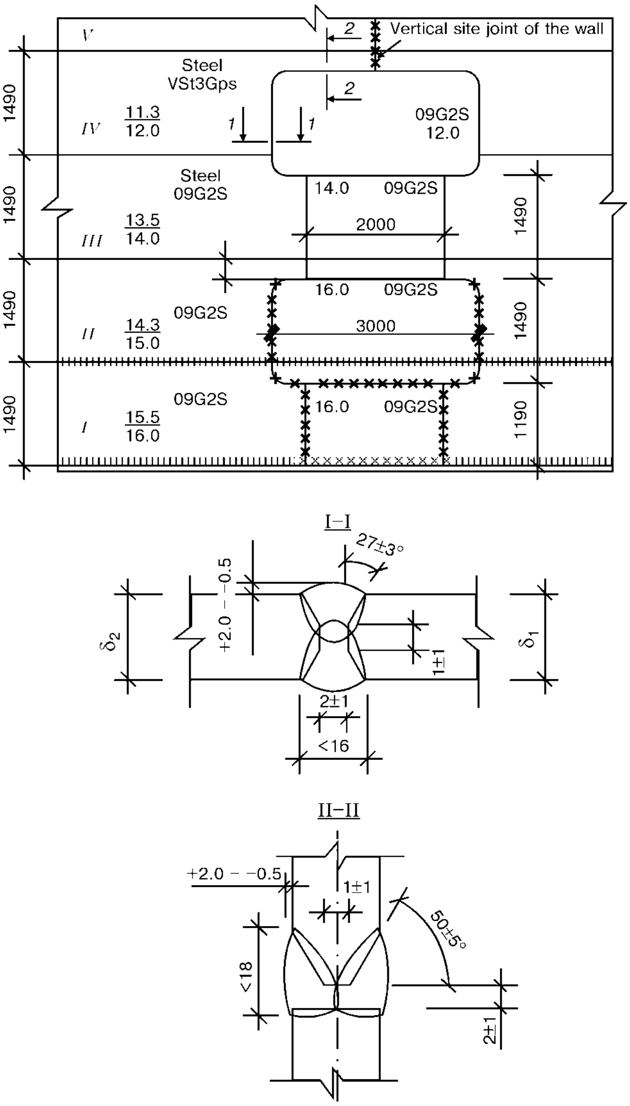

Figure 1. Schematic of welding-in rectangular inserts in the lower girths of a wall of 20 ths m^3 coiled tank: *I*–*V* — numbers of tank wall girths (the numerator gives the actual and the denominator — the design thickness of the sheet, mm)

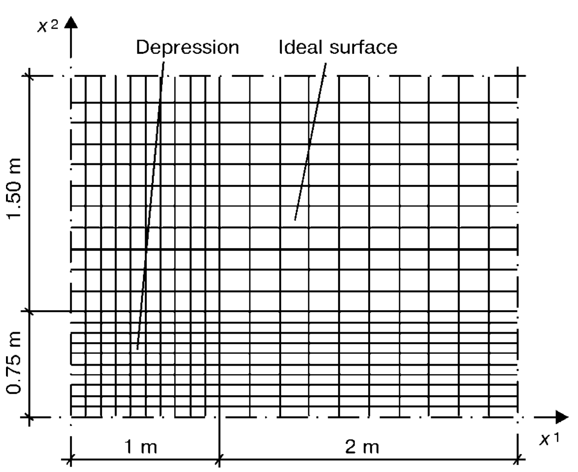

Figure 2. Difference grid of a cylindrical shell of a wall of a tank of r = 19950 mm with a rectangular-shaped depression

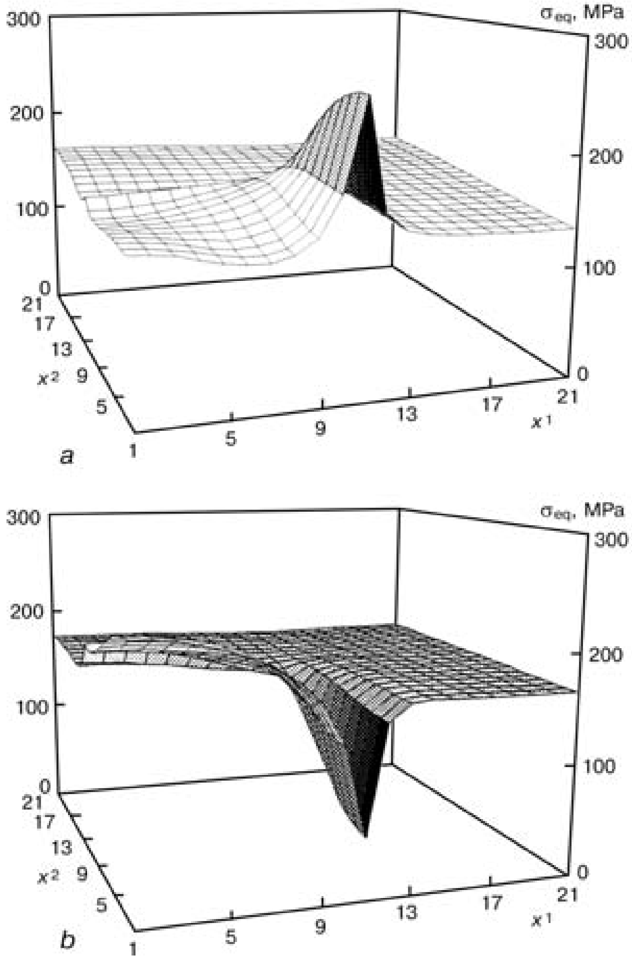

Figure 3. Fields of equivalent stresses in a cylindrical shell with a rectangular-shaped depression in the internal (*a*) and external (*b*) fibre (σ_{eq} — equivalent stresses)

tank of 20 ths m^3 capacity) with a rectangular-shaped depression (1500 × 2000 mm), to which a uniform internal pressure was applied. Conditions of symmetry of the fields of stress-strain state were assigned along the boundaries of this zone.

Calculation results showed that the maximum stress concentration develops on the vertical line of transition from the tank wall shell to the depression in the internal fibre (Figure 3, *a*), where the coefficient of stress concentration is equal to K = 1.6. This is attributable to the fact, that there is a kink in the surface in the area of transition from the shell to the depression, and as a result of tank filling with liquid, the depression straightening leads to appearance of maximum bending moments and corresponding stresses.

Another area of the insert, where increase of equivalent stresses is found, is the external fibre in the centre of the depression, where K = 1.35 (Figure 3, *b*). And although the stress concentration here is lower than on the transition line, the calculations, probably, should take into account the central region of the insert, as in the actual structure transition proceeds without formation of the kink, and stress concentration in the transition zone will be significantly lower than the calculated value.

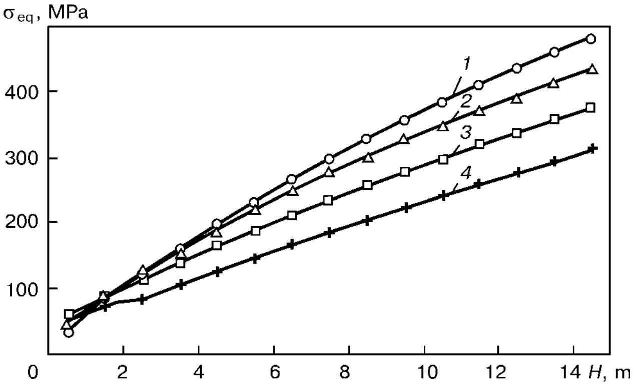

Figure 4. Dependence of equivalent stresses σ_{eq} in the internal fibre on the vertical line of transition on the oil level H at different depth of depression: *1* — a_0 = −10; *2* — −20; *3* — −30; 4 — −40 mm

Figure 4 shows the dependence of equivalent stresses (calculated by 4th theory) in the internal fibre on the vertical line of transition from the depression to the rest of the shell, on oil level. As is seen from the Figure, change of these stresses follows the linear law (except for the initial deformation stage).

In view of the fact, that in evaluation of additional stresses, it is rational to consider the central region of the depression, and also assuming the depression to be shallow and its transition to the cylindrical shell to be smooth, a simplified calculation procedure of a cylindrical shell with an imperfection may be analyzed. In a cylindrical shell of radius r the main force, balancing internal pressure q, is the circumferential tensile force, found from the following formula:

$$N = qr. \tag{3}$$

Let us replace the defective zone of the shell by a column with initial depth of depression a_0. This column is pivoted, has a unit width and length l and is loaded by tensile force N (Figure 5).

Let us formulate the equation of column equilibrium, proceeding from the conditions of the sum of internal and external moments being zero:

$$-EI\frac{d^2w}{dx^2} = N(a - w), \tag{4}$$

where E is the modulus of elasticity of steel; I is the moment of inertia of the column.

We will approximate the initial distortion and deflection of the column by a cosine half-wave:

$$a = a_0 \cos\frac{\pi x}{l}; \quad w = w_0 \cos\frac{\pi x}{l}. \tag{5}$$

Substituting expression (5) into the equilibrium equation (4), we get the following equation:

$$EIw_0\left(\frac{\pi}{l}\right)^2 \cos\frac{\pi x}{l} = N(a_0 - w_0)\cos\frac{\pi x}{l}.$$

Let us find its solution:

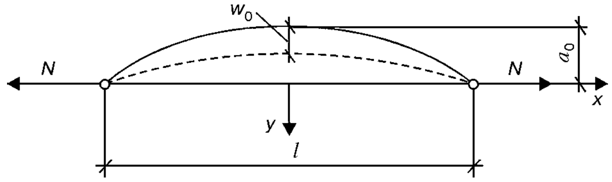

Figure 5. Column model (w_0 is the initial sag of the column)

$$w_0 = \frac{Na_0}{N + N_{cr}}, \tag{6}$$

where $N = \gamma Hr$ (here γ is the specific mass of liquid, contained in the tank); $N_{cr} = \pi^2 EI/l^2$ is the critical force of the pivoted column. In the column centre ($x = 0$) we will find moment M and maximum stress $\sigma_{c.m}$ according to column model:

$$M = \frac{\pi^2 EINa_0}{l^2(N + N_{cr})}; \tag{7}$$

$$\sigma_{c.m} = \frac{N}{\delta} + \frac{\pi^2 EINa_0}{l^2(N + N_{cr})}\frac{6}{\delta^2} = N\left[\frac{1}{\delta} + \frac{\pi^2 E\delta a_0}{2l^2(N + N_{cr})}\right]. \tag{8}$$

When the tank is filled with liquid with specific weight γ up to level H

$$\sigma_{c.m} = H\gamma r\left[\frac{1}{\delta} + \frac{\pi^2}{2}\frac{E\delta a_0}{l^2\gamma r(H + H_{cr})}\right], \tag{9}$$

where $H_{cr} = N_{cr}/\gamma r$ is the critical level of filling.

Comparison of equivalent stresses in the external fibre in the depression middle part, calculated, using the shell and the column models, shows that a good

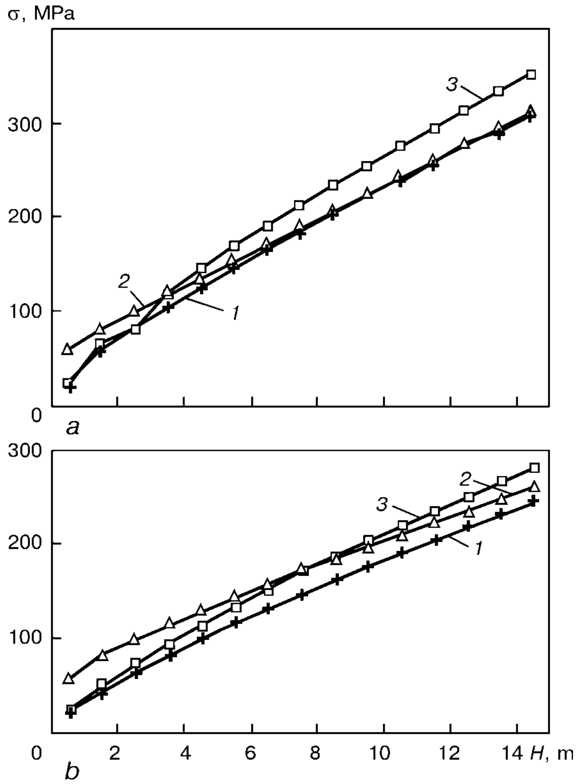

Figure 6. Comparison of values σ, produced using the shell and column models at a_0 = −20 mm and thickness of tank shell of 10 (*a*) and 15 (*b*) mm: *1* — equivalent stresses; *2* — stresses, found from column model; *3* — loop stresses

Table 1. Comparison of the results of calculation of equivalent stresses σ_{eq} in the external fibre, produced using SCAD, and stresses, calculated by column model $\sigma_{c.m}$

No. of tank girth	δ, *mm*	*H, m*	a_0, *mm*	σ_{eq}, *MPa*	$\sigma_{c.m}$, *MPa*	*Stress difference, %*
I	16	14.75	37.5	331*	299	10
IV	14	11.75	18.5	209	204	2
V	14	10.25	16.0	230*	197	15
VI	12	8.75	14.0	187	169	10

*Average magnitude of stress.

agreement of their values is found for the cylindrical shell 10 mm thick: difference is not more than 4 % at filling level above 7 m (Figure 6, *a*). For the case of the shell of greater thickness (δ = 15 mm), the accuracy of calculation, performed with the column model, is lower. However, at $H \geq 11$ m the difference between equivalent stress and stress in the column is not more than 10 % (Figure 6, *b*). As 14–17 mm thick sheets are used, as a rule, in the lower loaded girths, condition $H \geq 11$ m holds, and application of the column model for calculation is valid in this case. Dependence of equivalent stresses on oil level is close to a linear value for a cylindrical shell of 10 and 15 mm thickness.

Linear nature of dependence of stress values in the insert center and along the line of transition from it to the shell on oil level at different values of deviation of the depression shape from the design value, and, as shown by experimental studies, absence of insert twisting (just the curvature of the curve generator changes) allow taking the design length of the insert sag f_{des} (Figure 7) as the main characteristic of insert geometrical shape. Deviation of the geometrical shape of the insert, in its turn, will be characterized by value a_0, equal to the difference between the actual and design length of the sag (Figure 7).

Further checking of the accuracy of the proposed column model was performed for actual deviations of the geometrical shape of inserts, welded-in to replace the aligned vertical assembly joints by shifted joints in a tank of 20 ths m^3 volume [4]. Geometrical shape of the tank wall in this case meets the above requirements. In particular, additional stresses along the vertical line of transition from the insert to tank wall were absent, which allowed the column model to be applied. Comparison of equivalent stresses, calculated by the finite element method, using SCAD computing system [12], in the external fibre along the vertical axis of symmetry of the insert and magnitudes of stresses, calculated by the column model, showed them to be quite close — the difference being 10 % on average (Table 1).

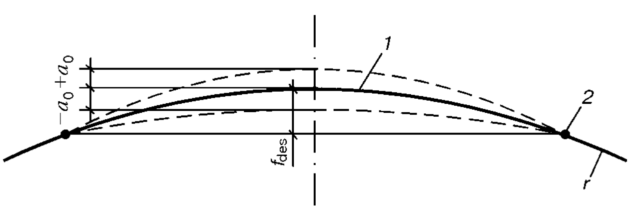

Figure 7. Determination of deviation of the geometrical shape of inserts from design position: *1* — design position; *2* — vertical welds

Thus, the results of the performed investigations indicate that the column model can be used to determine admissible deviations of geometrical shape of the inserts after welding-in. In this case, the following conditions should be observed: absence of abrupt kinks in the area of transition from the cylindrical shell to imperfections (along the vertical and horizontal lines); and the depression should be shallow.

Analysis of the dependence of magnitudes of additional stresses on insert length, determined using the column model (8), in the most loaded girth of the tank of the capacity of 20 ths m^3 (Table 2) showed that presence of even slight initial deviations from the design geometrical shape induces a significant stress concentration. The obtained result reveals the need for a highly accurate welding of inserts into the tank wall. It is further obvious from (see Table 2), that the results of measurement of insert deviations with a 1000 mm long gauge, may be used only for their initial assessment. In keeping with [3], for thickness of 6–12 mm the admissible clearance between the gauge and the wall is ≈ 14 mm, which in the case of an insert of 1000 mm length and 11.3 mm thickness, corresponds to the coefficient of stress concentration $K \cong 1.8$.

The following approach can be taken to determine the admissibility of insert deviation. Analysis of experimental data, obtained at the PWI on the actual sag values demonstrated that in practice an accuracy of $a_0 = \pm 7$ and ± 10 mm, respectively, is achievable for a 20 ths m^3 tank with 8–16 mm wall thickness

Table 2. Ratio of stresses, calculated by column model, to admissible loop stresses

a_0, *mm*	*Length of insert, mm*				
	1000	*1500*	*2000*	*2500*	*3000*
5	1.26	1.11	1.05	1.03	1.01
10	1.53	1.24	1.13	1.08	1.05
15	1.81	1.37	1.20	1.12	1.08
20	2.09	1.50	1.28	1.17	1.11
25	2.37	1.63	1.36	1.22	1.15
30	2.64	1.77	1.48	1.27	1.13

Note. The following data was taken for calculation: maximum oil level in the tank — 14700 mm; *IV* girth of a tank of VSt3Gps steel of 11.3 mm thickness; design resistance R_y = 225 MPa; γ_c = 0.8.

and 19950 mm radius, when welding-in inserts of 2000 and 3000 mm length. Such deviations should not cause any significant additional stresses. Assuming, that appearance of local additional stresses is caused by bending, their admissible values should, probably, be limited by 5–8 % of values of loop stresses. If the inserts are made of stronger steel that the respective girth, the values of additional stresses can be determined, taking into account the ratios of their design yield points. Proceeding from the above, we may write

$$\sigma_{c.m} \le \gamma_c \gamma_{depr} R_y, \qquad (10)$$

here γ_c is the coefficient of the operating conditions of tank girth, found in keeping with [13] or [3]; γ_{depr} is the coefficient, defining the admissible values of additional local stresses in the insert (depression) in relation to loop stresses and taken to be 1.05–1.08 or $\gamma_{depr} = R_{y\ \mathrm{insert}} / R_{y\ \mathrm{girth}}$ (here R_y is the design resistance of the steel girth/insert by yield point).

We will determine from expression (10) in view of (9) the admissible deviation a_0 from design value:

$$a_0 \le \frac{2l^2\,(1 + H_{cr}/H)}{\pi^2 E \delta}\,\gamma_c\,\gamma_{depr} R_y - \frac{H\gamma r}{\delta}. \qquad (11)$$

Let us evaluate the values of additional stresses in the most loaded *IV* girth of tank RVS-20000 SKP No.11 of NPS «Avgustovka» Branch of Company «Ukrtransnafta» (Table 2) for the above deviations of the sag: at insert length of 2000 mm additional stresses are 8 % ($\gamma_{depr} = 1.08$), and at insert length of 3000 mm — 5 % ($\gamma_{depr} = 1.05$). If we assume, that $\gamma_{depr} = 1.08$ at insert length of 3000 mm, admissible deviations of the geometrical shape of inserts, calculated by (11), will be $a_0 = \pm 15$ mm. For other, less loaded girths, the selected tolerance provides lower values of equivalent stresses, which do not exceed admissible magnitudes of loop stresses — $\sigma_{c.m} \le \gamma_c R_y$.

CONCLUSIONS

1. Evaluation of the stressed state of a cylindrical tank wall with rectangular inserts should take into account the concentration of stresses in the external fibre in the insert centre.

2. The main characteristic, defining the deviation of the geometrical shape of a rectangular insert from the design shape, is the difference between its design and actual sag.

3. It is proposed to assume such values of admissible deviation of insert sag from the design value, which would provide additional stress values of not more than 5–8 % of those of admissible loop stresses.

4. A column model can be used to assign admissible deviations of the sag of a rectangular-shaped insert from the design value.

5. Development of a special welding technology, providing sufficiently high accuracy of welding-in the inserts, is required to achieve admissible deviations of inserts in practice.

1. Raevsky, V.G. (1946) New method of production of stationary welded tanks. *Avtogennoe Delo*, **5/6**, 17–20.
2. Biletsky, S.M., Golinko, V.M. (1983) *Industrial production of outsized welded sheet structures*. Kyiv: Naukova Dumka.
3. *VBN V.2.2-58.2–94*. Vertical steel tanks for oil and petroleum product storage at the pressure of saturated vapors of not more than 93.3 kPa. Introd. 01.10.94.
4. Barvinko, Yu.P., Golinko, V.M., Barvinko, A.Yu. (2001) Improvement of performance of vertical erection welded joints in the wall of cylindrical tanks made of coiled blanks. *The Paton Welding J.*, **7**, 27–32.
5. Pisanko, N.M. (1962) Complex solution of the problem of tolerances in manufacturing of vertical cylindrical welded tanks. In: *Transact. of V.V. Kujbyshev MISI*. Issue 18.
6. *SNiP II-V.5–62*. Metal structures. Manufacturing, mounting and acceptance regulations. Introd. 01.01.63.
7. Vaskevich, A.A. (1978) On additional stresses in metal tank elements. *Transport i Khranenie Nefti*, **6**, 15–19.
8. Katanov, A.A. (2000) Complex evaluation of stress-strain state of tanks using computer-aided procedures. In: *Abstr. of Int. Colloquium on New Solutions in Design and Construction of Steel Tanks*, Odessa, June 13–15, 2000. Kyiv: VAT UkrNDIproektstalkonstruktsiya.
9. Chernykh, K.F. (1964) *Linear theory of shells*. Part 2. Leningrad: LGU.
10. Gotsulyak, E.A. (2001) On grid digitization of vector relationships of theory of shells in a curvilinear system of co-ordinates. *Prikladnaya Mekhanika*, **6**, 89–94.
11. Bazhenov, V.A., Gulyaev, V.I., Gotsulyak, E.A. et al. (1987) *Stability analysis of complicated shape shells (Procedural guidelines on application of MEKRIS-2 program system)*. Kyiv: KISI.
12. Karpilovsky, V.S., Kriksunov, E.Z., Perelmuter, A.V. et al. (2000) *SCAD for user*. Kyiv: Kompas.
13. *SNiP 2.09.03–85*. Industrial buildings. Introd. 29.12.85.

WAYS OF INCREASING STRENGTH OF WELDED JOINTS IN TUBES OF THERMOPLASTIC MATERIALS (REVIEW)

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Methods for increasing strength of welded joints in tubes of thermoplastic materials are reviewed. These methods are based on removal of oxide film by shearing it during welding of plastics using IR-radiation, application of a profiled hot tool and mechanical stirring.

Key words: *welding, thermoplastics, IR-emitter, profiled hot tool, mechanical stirring*

Theoretical basis of scientific developments in the field of technology and equipment for welding plastics is investigation into the mechanism of formation of welded joints. It is reported [1] that interaction of edges of a polymer welded with a hot tool and ambient atmosphere during welding (as a result of thermal-oxidation destruction) leads to formation of a surface layer dramatically differing in its properties from the base material. This layer, i.e. a film, prevents joining of molten surfaces and may lead to complete or partial lack of fusion, which has a substantial effect on strength.

To provide a sound welded joint, it is necessary to remove ingredients formed on the surface of molten edges to intensify rheological processes within the contact zone. It is well known [2] that increase in thickness of the weld edges is accompanied by increase in time of heating. Thus, in preparation of edges for welding using IR-radiation, the time of heating for low pressure polyethylene (LPP) tubes with a diameter of 110 mm and wall thickness of $\delta = 10$ mm is no more than 19 s, whereas for the LPP tube with a diameter of 800 mm and $\delta = 26$ mm the time for penetration to a depth of 2 mm is 45 s. Naturally, in the second case the oxide film preventing welding is much stronger because of a longer oxidation period, and strength of a welded joint in this case is lower than in the first case. Therefore, welding of thick-walled elements by this method involves difficulties.

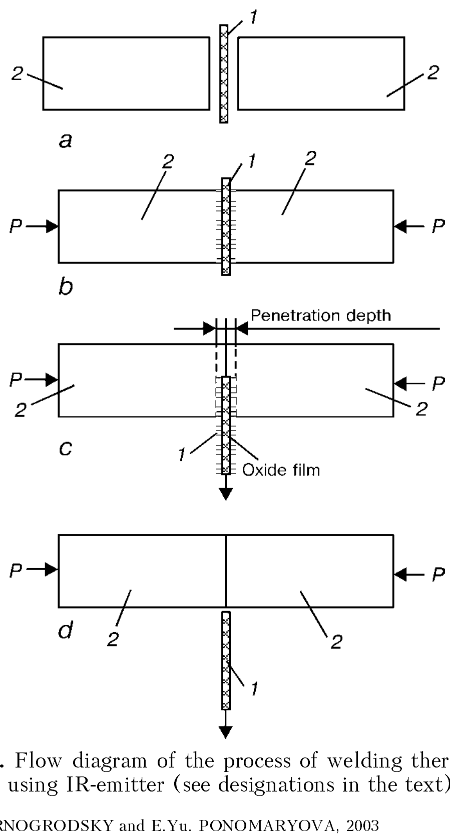

Figure 1. Flow diagram of the process of welding thermoplastic materials using IR-emitter (see designations in the text)

There are methods intended for destruction of oxide film during welding. They include, for example, oscillating one tube about its axis to 2–3° and reciprocating it relative to the axis to 2–3 mm during upsetting at a frequency of 3–5 Hz [1]. A drawback of these methods is that they require special mechanism to induce oscillating or reciprocating motion.

The E.O. Paton Electric Welding Institute of the NAS of Ukraine developed and tested the method for removal of an oxide film during welding of plastics using IR-radiation. Peculiarity of its application is as follows. IR-emitter *1* (Figure 1, *a, b*) is introduced into a gap between weld edges *2* to penetrate them to a required depth. Then the weld edges are pressed to the IR-emitter, and the hot tool is gradually withdrawn without relieving the upsetting pressure (Figure 1, *c*). Temperature of the hot tool at the moment of pressing should be lower than the ignition point. Material is not ignited at this temperature, whereas the oxide film adheres to the surface of the hot tool by sintering. Then, as the hot tool is withdrawn, the film is sheared from the weld edges (Figure 1, *d*), and their upsetting is performed.

This method was tested in welding of elements of the LPP tube with a diameter of 800 mm and wall thickness of $\delta = 26$ mm. Samples were $65 \times 26 \times \times 80$ mm in size. A prototype of the IR-emitter was made by the PWI. It is a nichrome plate 1 mm thick and 40 mm wide. The emitting surface temperature is 850 °C. The IR-emitter is introduced into the centre

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of the 20 mm gap between the edges to be welded. After the surface layer of the edges is penetrated to a depth of 2 mm (time of heating the edges is 45 s), the hot tool is switched off from the power supply and allowed to cool down for 2 s to a temperature below the ignition point (for LPP this temperature was assumed to be equal to 500 °C). Then the tube edges are pressed to the hot tool with an upsetting pressure of 0.02 MPa. At a temperature of 500 °C the oxide film adheres to the hot tool as a result of sintering. After 2 s, without relieving the upsetting pressure of 0.02 MPa, the hot tool is gradually withdrawn at a speed of 2 cm/s, and then the upsetting pressure is increased to 0.2 MPa.

During the withdrawal process the hot tool shears off the oxide film adhering to it. When the hot tool is switched on again, the film and the material that stuck to it are burnt away, i.e. self-cleaning takes place, which means that no anti-adhesion layer and no special cleaning are required.

The resulting welded joint was tensile tested. As shown by the tests, the mean value of strength of the weld is not lower than that of the base material. This is explained by the fact that the mating surfaces were non-oxidised, thus the welded joint was not weakened by the oxide film, which is the case of other known welding methods using the IR-emitter. The load-carrying capacity of the material can be fully utilised owing to the fact that the welded joint has strength equal to that of the base material.

Another important factor which determines strength of the welded joint is stirring of the melt of the mating surfaces during welding. This stirring favours equalisation of physical parameters of the solidifying material, breaking and partial removal of harmful impurities from the welding zone, which leads to increase in strength of the weld.

In the 1960s K.I. Zajtsev put forward a «rheological» concept of the mechanism of formation of welded joints in plastics. According to this concept, rheological processes occurring in the zone of contact of the parts to be joined play a substantial role in the mechanism of formation of welded joints. The surface of the hot tool is made rough to increase strength of the weld due to a more comprehensive stirring of the base material. This surface may have peaks and valleys looking like a fabric weave pattern [3]. It was suggested that, after the end of heating of the weld edges and withdrawal of the hot tool from the gap between the edges, i.e. during upsetting, the parts to be joined should be moved relative to each other and parallel to the plane passing through their edges. Owing to such an oscillation movement, the material heated to a plastic state is intensively stirred, and strength of the weld material is thus increased. A drawback of this method is that it is difficult to induce oscillations. In addition, to withdraw the hot tool it is necessary to draw the mating surfaces apart, which results in their oxidation. Some of the oxidation products remain in the weld, thus decreasing strength of the welded joint.

The efficiency of stirring can be increased by changing the shape of the edges prior to welding (by machining) or by heating (melting) them using a shaped hot tool. An example is a tool for resistance welding [4], the working surfaces of which are profiled in such a way that they have a saw-toothed shape in their cross section, and the height of the teeth and distance between them may be varied from 0.5 to 3 mm. Drawbacks of such a hot tool are a sophisticated technology used to manufacture it and decrease in strength of the welded joint as a results of the oxidation products formed during the process pause, which get into the weld.

Available is the method for welding polymeric materials which prevents ingress of the oxidation products into the weld [5]. The hot tool, i.e. a metal plate (blade), is placed between the parts to be joined. After the heat from the plate softens the surfaces pressed to it, the plate (blade) is rapidly withdrawn without drawing the edges apart. A device was offered for butt welding of thermoplastic tubes by using this method [6]. However, because welding is performed only due to a contact of the surfaces activated by heating, strength of such a welded joint is insufficient.

Strength of welded joints can be increased by using a profiled hot tool, in which a ridge of each peak and ends of each valley form a closed loop (Figure 2). Hot tool *1* is made from a heat-conducting material (of the type of aluminium), and the working surface of the tool is covered by anti-adhesion layer *2*. The number of the loops depends upon the thickness of the parts to be joined, while the distance between the ridges of the neighbouring loops may be varied from 0.5 to 3 mm. The hot tool can be heated using any power supply.

The device works as follows: edges of the parts joined are pressed to the profiled hot tool preheated to a required temperature, and heated to form the matching pattern of peaks and valleys. At the same time, the material is heated to a certain depth, the hot tool is withdrawn, and the parts are joined together under a pressure. The peaks enter the valleys simultaneously over the entire surface and press out the melt, which is displaced from the centre of the section to its ends. No lateral movement along the ridge results from the simultaneous pressing of the melt in a closed loop, and the melt flows normal to the ridge axis, being displaced under pressure along the wavy gap formed between the parts joined. A drastic change in the direction of movement of the melt is characterised by a turbulent flow promoting stirring of the melt of the parts, while an elongated path of movement of the melt, compared with welding using a flat hot tool, raises the probability of formation of chemical bonds between materials of the parts. All this leads to increase in strength of the resulting welded joint. The samples welded using the profiled

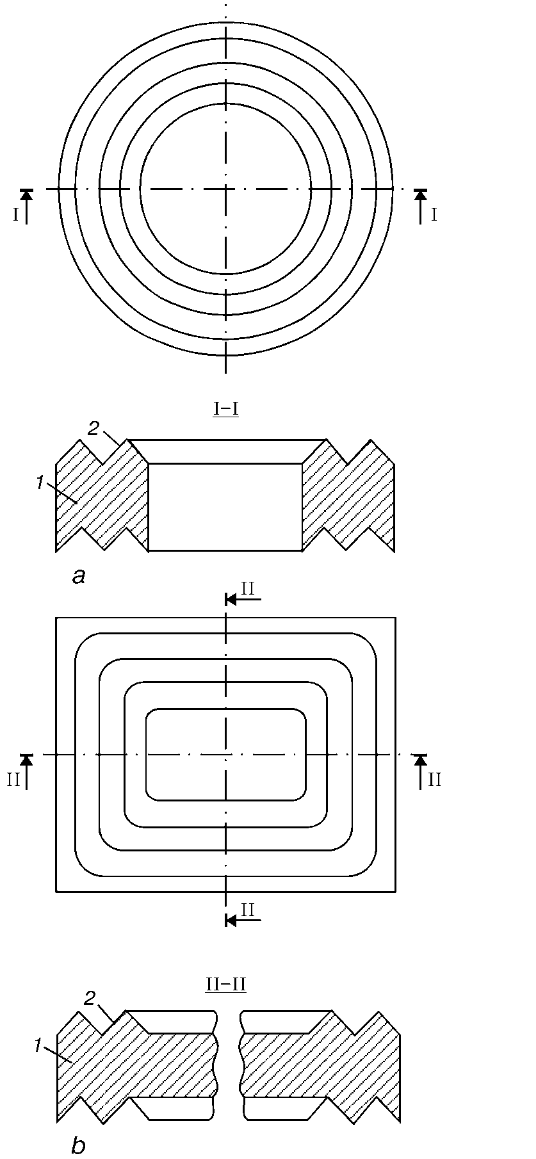

Figure 2. Schematic of the profiled hot tool for welding cylindrical parts (*a*) and parts of a rectangular section (*b*): *1* — hot tool; *2* — adhesion layer

hot tool fractured during the tensile tests mostly in the base material. For a PVC tube σ_t = 43.4 MPa.

The PWI developed a device for welding thermoplastic materials, intended for increasing strength of welded joints, especially in hard-to-weld plastics. The device provides intensive mechanical stirring of the melt during welding [7]. The hot tool of the above device comprises two thin movable plates with a comb having helical teeth made on their tips. The teeth provide mechanical stirring of the material of the mating surfaces pressed to each other during withdrawal of the tool. The hot tool is made from a material with a high-ohmic resistance (of the type of nichrome) and is covered with an anti-adhesion layer.

The device for butt welding of thermoplastic tubes is shown in Figure 3. The tip of plates *1* and *2* of the hot tool ends with a comb, teeth *3* of the comb being turned about their longitudinal axis in such a way that they form a helical surface. The upper edge of

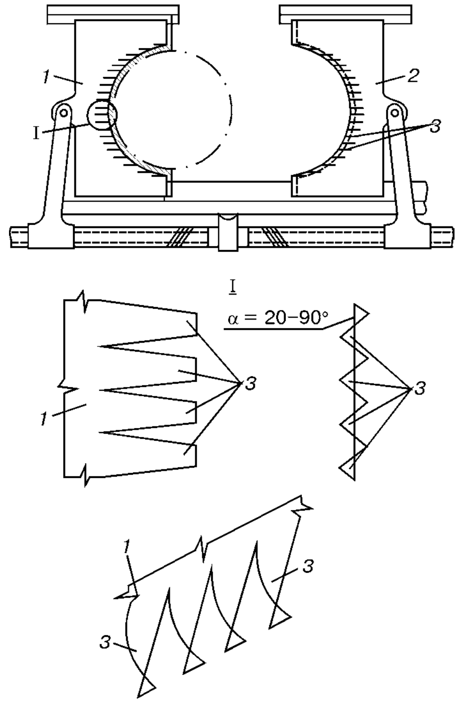

Figure 3. Schematic of device for butt welding of thermoplastic tubes (see designations in the text)

each tooth is turned relative to the plane of the hot tool to an angle of α = 20–90°, i.e. angle between projection of the tooth edge and projection of the plane of the hot tool on a plane normal to the hot tool (Figure 3, unit I). Angle α is formed as a result of twisting of the edge of the tooth about its longitudinal axis. In this case its lateral faces acquire a helical line shape as a result of plastic deformation. During withdrawal of the hot tool the teeth enter into the molten material and stir it by the plough effect method (Fi-gure 4). A compressed zone of the molten material is formed under the helical surface of teeth *3* in movement of the hot tool, and the rarefied zone is formed over the teeth. Therefore, the melt flows from the compressed zone to the rarefied one, i.e. the melt of one edge welded flows to the zone of the other edge and vice versa, thus enhancing the effect of stirring and increasing strength of the welded joint.

It was experimentally found that the efficient stirring of the melt of a polymer welded with the comb teeth begins at an angle of α = 20°. Increase in the angle α is accompanied by increase in dimensions of the teeth from the plane of the hot tool. At the same time, this leads to increase in projection of the tooth

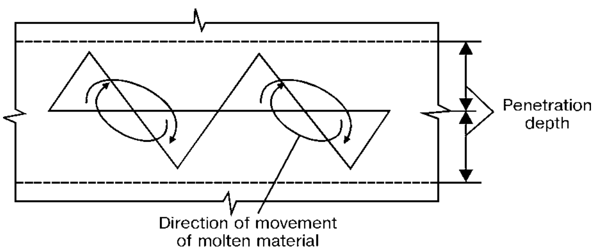

Figure 4. Schematic of mechanical stirring

area on the plane normal to the plane of the hot tool, i.e. increase in the stirring zone area. This area, which (for each tooth) is the area of two isosceles triangles (see Figure 3), amounts to its maximum value at $\alpha = 90°$. Increase in angle α from 0 to 90° leads to increase in the force needed to withdraw the hot tool. Different stirring volumes are required for different polymers to produce a welded joint with strength equal to that of the base material. Optimal technological and strength parameters can be achieved by varying angle α.

Elements of a PVC tube 110 mm in diameter were welded using the above hot tool. For this, the hot tool had an angle of turning of the upper edge of the teeth relative to the plane of the tool equal to 45 and 60°. Tensile tests of the resulting welded joints and base material were performed using the ZD-10/90 machine. The deformation rate used was 20 mm/min. The mean values of tensile strength obtained at the identical welding parameters (pressure 0.2 MPa, hot tool temperature T_h = 250 °C) were σ_t = 45.2 and 41.7 MPa, respectively. This shows that the hot tool with an angle of turning of the teeth equal to $\alpha = 45°$ provides a stronger welded joint. Most specimens fractured in the base material. Welding (at the identical parameters) of the PVC samples using a similar hot tool but without teeth for stirring yields a mean value of tensile strength of a welded joint equal to no more than σ_t = 34.8 MPa at σ_t = 45.4 MPa for the base material.

CONCLUSIONS

1. Three methods are available for increasing strength of welded joints due to destruction of a surface layer at the tube edges. They are based on heating the edges using IR-radiation, application of a profiled hot tool and intensive mechanical stirring of the melt during welding.

2. Removal of ingredients from the weld edges, as well as intensification of rheological processes within the joining zone, increases weldability of thermoplastic materials.

3. Mechanical stirring of the melt allows strength of a welded joint to be increased to a level of the base material, which is especially important for welding parts of hard-to-weld thermoplastic materials, e.g. PVC.

1. Zajtsev, K.I. (1976) Resistance butt welding of high-density polyethylene tubes. *Avtomatich. Svarka*, **12**, 32–33.
2. Zajtsev, K.I., Matsyuk, L.N. (1978) *Welding of plastics*. Moscow: Mashinostroenie.
3. Tobias, W., Steinicke, H.-E. *Verfahren zum Stumpfschweißen thermoplastischer Halbzeuge und Formteile*. Pat. 135810 DDR. Int. Cl. B 29 C 27/06. Publ. 30.05.79.
4. Schwarz, H., Tobias, W. *Heiselement Schweißwerkzeug*. Pat. 106590 DDR. Int. Cl. B 29 C 27/02. Publ. 26.06.74.
5. Nikolaev, K.I., Olshansky, N.A. (1975) *Special welding methods*. Moscow: Mashinostroenie.
6. Vende, E.A. *Device for butt welding of thermoplastic tubes*. USSR author's cert. 448139. Int. Cl. B 29 C 27/06. Publ. 1974.
7. Tarnogrodsky, V.P., Korab, G.N., Koloskova, E.Yu. *Device for butt welding of thermoplastic materials*. USSR author's cert. 1052402. Int. Cl. B 29 C 27/06. Publ. 1983.

COMPETENCE OF PERSONNEL IS AN IMPORTANT COMPONENT OF THE SYSTEM OF ECOLOGICAL SAFETY OF WELDING PRODUCTION*

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Experience of interaction of Russian Research and Development Welding Society with similar world-level European structures in the field of personnel training is described. Coordinating role of the Inter-State Council for Welding and Related Technologies is shown. Provisions of the European certification schemes on quality and environment management systems are given.

Key words: *welding production, ecology, non-profit organisations, personnel, integration, certification*

Russian Research and Development Welding Society (RRDWS) was founded ten years ago as a professional association of welding specialists to represent interests of organisations and enterprises, companies, small businesses, as well as specialists involved in science, production and education in the field of welding and related technologies for different regions and industries relating to production and exploitation of welding structures.

The main objective of RRDWS is to protect principles of freedom of scientific and technical creative work, protect rights, legal interests and intellectual property of its members, form a material and social basis for realisation of their creative and professional potential for the benefit of progress of welding science, technology and production.

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The basic charter objectives of RRDWS include formation and harmonisation of standards and codes, certification of welding consumables, technologies and equipment, development of methods for ensuring environmental safety of production, methods for testing welding structures etc., as well as participation in development of measures for fulfilment of Russian, European and international standards and codes.

At present RRDWS is an official and active member of a number of non-governmental Russian and international organisations, such as International and Russian Unions of Scientific and Engineering Organisations, Inter-State Council for Welding and Related Technologies, International Institute of Welding (IIW) and European Welding Federation (EWF). Under an agreement with Gosstandart (State Standard), RRDWS participates in the International Standardisation Organisation (ISO) and has agreements on cooperation with similar non-profit organisations of Germany, France, USA and other countries.

The activity of IIW and EWF is gaining a special topicality nowadays in view of integration of national systems of ensuring quality in welding production into a unified international system formed on the basis of mutual recognition and cooperation, which has been confirmed by corresponding regulatory documents. The leading role of IIW and EWF in the scientific-and-technical cooperation is determined by the following goals and objectives of these organisations:

• exchanging of scientific and technical information and ensuring of dissemination of knowledge in the field;

• development of recommendations, preparation of reviews of the state-of-the-art and guidelines in the field of application of welding and related processes;

• rendering assistance with all available means in foundation of national welding institutes or welding societies in countries which have no such organisations;

• arranging of congresses, international conferences and regional meetings;

• development of specifications and guidelines for education, training, qualification and certification of welding personnel, as well as rules for application of these documents;

• preparation for and assistance in working out of international standards in collaboration with ISO;

• ensuring and stimulation of developments on environment protection.

Results of cooperation of RRDWS with international organisations are indicative of the efficient utilisation of the world-level experience in integration of European countries in the field of science and technology, standardisation, training, qualification and certification of personnel, environment protection, development and application of quality systems etc. To realise such an integration, the corresponding coordinating committees, task groups and commissions are being founded in accordance with all of the above directions.

Special attention is given to collaborative plans on working out of regulatory documents and standards covering all the basic areas of development of technologies, welding consumables, equipment, design and exploitation of welded structures.

The IIW and EWF member countries implement the procedure of certification of welding fabrications on the basis of standards ISO 3834 in full correspondence to the basic provisions of standards of the ISO 9000 series.

The integration resulted in formation of a unified structural division of IIW and EWF to deal with training, qualification and certification of welding personnel. The General Assembly of IIW at the 53rd Congress in 2000 affirmed a decision on foundation of the International Body for Certification of Personnel, which would unify into one system the IIW and EWF systems of education, training and qualification of welding personnel.

The special role in coordination of these efforts is played by the Inter-State Council for Welding and Related Technologies. Its last Meeting «Current Problems in Increasing Life and Operational Reliability of Welded Structures, Constructions and Equipment» took place in November 2001 at Research and Production Company «TsNIITMASh». Co-sponsors of this Meeting were the Inter-State Council for Natural and Technogenous Emergency Situations, Task Group at the President of the Russian Academy of Sciences for analysis of risk and safety issues, RRDWS and Russian Society of Non-Destructive Testing and Technical Diagnostics. The Meeting was chaired by Prof. B.E. Paton, the President of the National Academy of Sciences of Ukraine, Chairman of the Inter-State Council for Welding and Related Technologies and Academician of the Russian Academy of Sciences. The Meeting was attended by academicians and corresponding members of the Russian Academy of Sciences and National Academy of Sciences of Ukraine, experts of RRDWS and Russian Society of Non-Destructive Testing and Technical Diagnostics, representatives of scientific communities of Belorus, Kazakhstan and Georgia. 11 presentations were made, dedicated to different aspects of the problem in the field of power generation, transport, chemical and petrochemical engineering and other industries.

Because of an increasing number of technogenous disasters taking place throughout the world, the focus of specialists was on investigation of their causes, as well as search for methods for their timely prevention. The resolution made at the Meeting provides for widening of the inter-state program «Development of World-Competitive Welded Structures, Resource-Saving Technologies, Materials and Equipment for Welding Production» by including into it new projects and tasks aimed at handling the problems of estimation and extension of life of critical structures, constructions and equipment.

The following top-priority problems, requiring immediate solutions at the national and international levels, were distinguished at the Meeting:

• development of the regulatory basis for substantiated handling of problems associated with estimation and extension of life of critical objects by using the advanced technical diagnostics facilities and methods;

• improvement of the system of state inspection bodies specialising in types of technogenously hazardous objects by vesting them with functions of collecting, systematising and analysis of the information on a technical state of the above objects and development of recommendations for their safe exploitation;

• arrangement of the international system for training and re-training of personnel involved in welding production, technical diagnostics, non-destructive testing, estimation and extension of life of structures and equipment.

In view of the importance of the environmental safety problems, the federal law «On Environment Protection» was passed in the Russian Federation on the 20th of February, 2002. This is the first law that specified provisions for ecological certification (Article 31). In this case it is worthwhile to give the full text of this article to show directions of further efforts to be made proceeding from common interests of every human individual and society as a whole.

«Article 31. Ecological Certification.

1. Ecological certification shall be performed with a purpose to ensure an ecologically safe implementation of economic and other activities in the territory of the Russian Federation.

2. Ecological certification can be either mandatory or voluntary.

3. The mandatory ecological certification shall be performed in compliance with the rules specified by the Russian Federation Government.»

At the same time, there is an active discussion of the draft law «On Principles of Technical Regulation in the Russian Federation» at the government level in Russia. The draft document provides for adoption of technical regulations aimed at protection of life and health of individuals and environment, by realising in the above documents the mandatory rules and regulations in the fields covered by the law.

In this connection, RRDWS supported an initiative set forth by 26 countries — members of EWF to discuss and adopt a series of regulatory documents which could serve as the basis for drafting the technical regulation on special requirements to processes (methods) of fabrication, exploitation and disposal of various-application welded structures.

The main advantage of the scheme of voluntary (or mandatory) ecological certification suggested by EWF is that it is closely related to the system of training, qualification and certification of welding personnel which has been practically applied for not less than ten years.*

According to the suggested schemes and allowing for the experience of working with welding personnel, as well as for the results of certification of enterprises to fit requirements of standard ISO 3834 (EN 729), provisions are made for formation of an independent certification body in each country to combine functions of certification of quality systems and ecological management systems. This statement of the problem makes us return again to the issues of preparedness and competence of the personnel intended for practical application of these schemes. In this connection, it is expedient to cite formulations of standards ISO 9001–2000 and 14001–98 (Table) concerning requirements for competence of the personnel, which in our opinion is decisive for implementation of the state and in-house policies in the field of protection of the human living and production activity environment.

As follows from the experience in training, qualification and certification of welding personnel, the main part of the system of professional relations now belongs to procedures of training and assessment of competence of the personnel responsible for implementation of the quality and environment protection systems.

We are facing now the situation where the CIS countries, despite their ample experience in fabrication and exploitation of critical welded structures, may be among the countries that lag behind in realisation of the basic principles of environment protection accepted by the international community.

Development of certification schemes of the quality and environment protection systems in the CIS countries through the appropriate authorised national bodies should be based on the «Professional Behaviour Rules», a document approved by EWF (EWF-514–01). Consider a number of provisions of this document.

All the information given as the basis for certification and its confirmation should be correct and not misleading.

A certificate should be used only within the framework of certification and in a way provided for by certification.

Persons who passed certification should take all measures to confirm the fact that they perform their professional duties in an objective, comprehensive and competent way to guarantee safety of all of the rest of the people, be aware of the latest achievements in those fields of technology where their professional activity belongs, and fix all the complaints made on them in the field their certificate covers.

Persons who passed certification and/or their employers should not use the certificate or its part (or

* (2000) Bernadsky V.N., Makovetskaya O.K., Protsenko P.P. *Modern European and International system of education and training of welding personnel: PWI Review*. Kyiv: PWI. 20 pp.

ISO 9001–00	ISO 14001–98
6.2. Human resources	
6.2.1. General provisions Personnel performing the work which affects quality of products should be competent to comply with the education, training, skills and experience it has received.	
6.2.2. Competence, knowledge and training Organisation should: a) assess the required competence for personnel performing the work which affects quality of products; b) provide training and make other arrangements to meet the above requirements; c) estimate results of the arrangements made; d) keep its personnel informed of the topicality and importance of its activity and contribution to achievement of purposes in the field of quality; e) keep the records of education, training, skills and experience of its personnel constantly updated.	4.4.2. Training, knowledge and competence Organisation should identify its demands for training of personnel. It should require that all the personnel performing the work which may substantially affect environment have the appropriate training. Organisation should establish and keep updated all the procedures which allow its employees or staff of each of its appropriate divisions and levels to understand: a) importance of compliance with the ecological policy, procedures and requirements of the environment management system; b) substantial, actual or potential effects its activity may have on environment, as well as benefits of improving personal efficiency for environment; Personnel performing the work which may have a considerable effect on environment should have competence in compliance with corresponding education, training and practical experience.

consciously allow it to be used) in a way which can be considered fraud, unreasonably refer to the certification scheme or use the certificate in a misleading way in advertising, catalogues etc.

Refusal to follow the above Rules may lead to withdrawal of the certificate.

Ethics of professional behaviour also determines the requirement for an open and true information to be provided to all interested parties on the correspondence of the certification and/or qualification schemes to international standards, codes and regulations.

SPECIAL FEATURES OF DESIGNING MECHANISMS OF PULSED FEED OF ELECTRODE WIRE IN WELDING EQUIPMENT

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Some features of development and design of mechanisms of pulsed feed of electrode wire are described. Serious problems are considered, arising at high accelerations in the pulse and at variable feed rates, which consist in the need to reproduce the pulse parameters, set by the electrode wire at its interaction with the feed rollers, lowering the level of mechanism vibrations, affecting the mechanical reliability of the mechanism and the conditions of conducting the welding process. Methods to improve the operating conditions of pulsed feed mechanism are demonstrated.

Key words: *arc welding, mechanized equipment, feed mechanism, electrode wire, pulse*

Improvement of mechanized arc welding equipment, designed for welding and surfacing both in shielding gases, and using self-shielded flux-cored electrode wires, is always related to design of feed mechanisms. Use of pulsed mechanisms of wire feed provides an integral solution of the problem of improvement of the entire feed system, which is favourable for the technological process.

There exist several types of pulsed feed mechanisms, which in this work are grouped in a certain fashion, depending on the type of the design of the mechanical devices, converting the motion of the drive into the translational motion of electrode wire. These mechanisms make reciprocal motion, transferred by a certain algorithm to one-sided grips — electrode wire movers [1, 2]. The paper presents a group of mechanisms with conversion of motion from the drive (using electric motors), which, in their turn, could be divided into two large groups, namely with transfer of motion to one-sided grips [3] and to feed roller [4]. However, the published data on application of such mechanisms are insufficient for development of an optimal system of pulsed wire feed.

The purpose of this work is to substantiate selection of mechanism designs, providing a reliable pulsed feed of the wire with specified parameters as part of the equipment for mechanized welding.

Problem 1. *Optimizing the clamping device for feeding by the roller mechanism of electrode wire, moving at high accelerations with implementation of pulsed feed or at abrupt changes of the rate (start or application of current modulation) in a regular feed mechanism.*

The problem of optimization of the clamping device consists in improvement of the efficiency of electrode wire feed mechanism, reducing wire deformation in the zone of contact with the rollers, lowering the probability of slipping of the feed roller relative to the wire with loss of specified motion parameters, determining the quality of the technological process [5].

Let us consider the forces, acting during wire feed (Figure 1). A condition of reliable feed of the wire may be written [6] as

$$F_f > F_r, \tag{1}$$

where F_f is the feed force, transferred by feed roller to the wire; F_r is the total (static and dynamic) condition of resistance to wire motion.

Force F_f of wire feed is due to a number of factors, which with a certain simplification of physical phenomena in the contact zone may be united by the following equation:

$$F_f = bF_{cl}/f, \tag{2}$$

where b is the margin of adhesion to achieve reliable feeding, provided by special contouring of grooves, knurling, expansion of the feed roller surface, etc.; F_{cl} is the force of feed roller clamping; f is the coefficient of friction of the wire and roller materials.

We will rewrite condition (1), in view of equation (2), in the following form:

$$bF_{cl}/f > F_r. \tag{3}$$

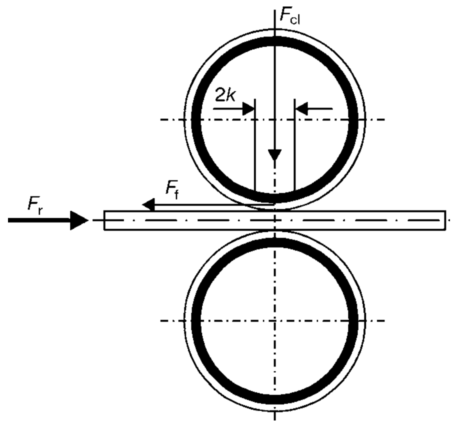

Figure 1. Forces, acting in the zone of contact of feed and press-down rollers in electrode wire feeding

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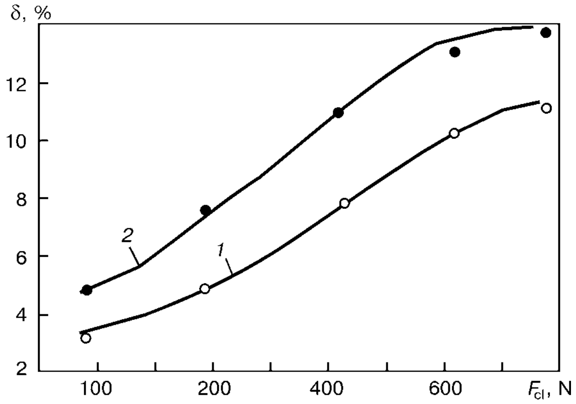

Figure 2. Dependence of relative losses δ in roller feed unit on clamping force: *1* — smooth feed roller; *2* — feed roller with a wedge-shaped groove

Analysis of condition (3) indicates that feed force F_f = var and depends not only on clamping force F_{cl} = = const (i.e. is selected for the given conditions of wire feed), but also on the coefficient of friction f, which is a multifactor quantity and is determined by a number of parameters, i.e.

$$f = f(f_q, f_s, f_r, t_d, v_f, v_s),$$

where f_q, f_s, f_r are the coefficients of friction of quiescence, slipping and rolling, respectively; t_d is the dwell time of the roller with wire; v_f is the rate of wire feed; v_s is the rate of roller sliding relative to the wire.

It does not seem possible to take into account the influence of all the parameters on f, therefore under the actual conditions of feed mechanism operation, the claming force is set to be deliberately great, so as to avoid variations of f and F_r. This leads to an increase of losses in the feed unit, wire deformation, increase of drive power, designed for long-time higher load. Mechanism efficiency drops considerably, because of the loses, arising in the zone of friction contact of the metal of rollers and wire to include: hysteresis losses δ_h at roller rolling over the wire, resulting from deformation of the latter by the roller under the impact of the clamping force, increasing with increase of this force as a result of a longer arm of rolling friction k, schematically shown in Figure 1; slip losses δ_s, in this case geometrical, due to non-uniform variation of the rate along the line of contact with roller profiling, inaccuracies of their mounting or fabrication and increasing with the increase of the camping force; losses in bearing δ_b of press-down roller, as well as in bending of axes of the feed and press-down rollers under the impact of the clamping force.

If losses are to be determined in relative units, the efficiency of the feed assembly η may be calculated as follows:

$$\eta = 1 - (\delta_h + \delta_s + \delta_b).$$

The author performed experimental evaluation of total relative losses δ ($\delta = \delta_h + \delta_s + \delta_b$) in the roller feed mechanism of PDG-516 semi-automatic machine with two types of rollers, namely with a smooth surface and a wedge-type groove at change of clamping force. Evaluation results for Sv-08G2S wire of 1.2 mm diameter are shown in Figure 2. The shape of both the dependencies is practically the same, but in the case of a grooved roller, the losses are somewhat greater, which, in the opinion of the author, results from great losses for slipping of the wire along both walls of the wedge-shaped groove. At considerable clamping forces, the losses are stabilized, because of a low increment of contact deformation.

Thus, in order to minimize the losses in the roller feed unit, it is rational to ensure the following condition:

$$F_f / F_{cl} = \text{const}. \tag{4}$$

Condition (4) is difficult to ensure, in particular, because of the presence of a long flexible guide [7]. For its implementation, the PWI manufactured and developed an experimental device, mounted in the feed system of the semi-automatic welding machine. Regulator device (Figure 3) performs automatic selection (regulation) of the force of wire clamping by the press-down roller, depending on the force of feed resistance. Let us consider the operation of the above regulator.

Fastened on shank *3* of hose holder *1* is thrust ring (nut) *4*, as well as grooved press-down element *6* with angle of inclination α, aimed oppositely to the electrode wire motion (arrows indicate the direction). Hose holder *1* is spring-loaded relative to case *5* by cylindrical spring *2*, where the force is assigned by the position of thrust ring *4*. Electrode wire *7* is clamped to feed roller *8* by press-down roller *9*, tied to one end of an elastic element, for instance flat

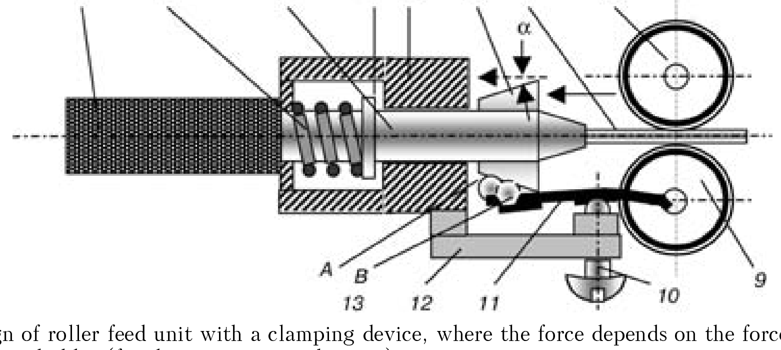

Figure 3. Variant of design of roller feed unit with a clamping device, where the force depends on the force of resistance to electrode wire feed in elements of hose holder (for designations see the text)

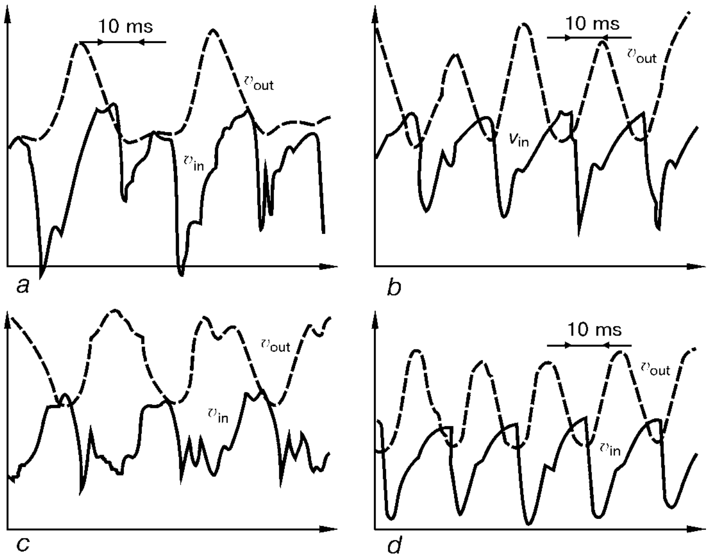

Figure 4. Characteristic oscillograms of the rates of pulsed feed of electrode wire (solid curve — at mechanism inlet, v_{in}; dashed curve — at guide outlet, v_{out})

spring *11*. Flat spring *11* is resting on adjusting element *10*, made in the form of a screw and located on bracket *12*. The other end of flat spring *11* is fitted with a sliding or rolling element *13* (sphere, as in our case, roller or bearing could also be used), which interacts with press-down element *6*. Setting up of the device consists in selection of initial force of spring *2*, providing motion of electrode wire in the mode without welding or manipulation of the holder. Sphere *13* together with one of the ends of flat spring *11* takes up position *A*. In this case sag of spring *11*, providing, according to condition (1), the required minimum force of electrode wire clamping down by roller *9*, is adjusted by screw *10*. If the force of resistance to the feed does not change, the clamping force is also unchanged. With the increase of the former above the force of spring *2*, translational motion of hose holder in the direction of electrode wire feed begins, sphere *13* moves into position *B*, causing greater sag of flat spring *11* and thus providing the increase of clamping force, required for this situation. The process is reversed with lowering of the force of feed resistance. Thus, the regulator automatically supports the ratio of forces in accordance with expression (4). This regulator was tried out in feeding flux-cored wires by rollers with smooth feed surfaces, preventing deformation of wire sheathes. Average values of losses in the roller unit per a welding cycle were reduced 2 to 4 times.

Regulator operation with pulsed wire feed was studied. Figure 4, *a, c* shows oscillograms of motion speed in operation of the mechanism with a pulsed feed with smooth rollers. No regulator was mounted in the system, represented by oscillogram 4, *a*. Here we can see slipping of the feed roller relative to the wire. Experimental study of the slipping phenomenon in the pulsed feed mechanisms led to the following conclusions. Wire clamping force, preset in the roller feed unit, at the first moment usually provides the conditions, required for its movement due to high enough values of *f* (friction of quiescence, absence of slipping). At increase of the pulsed circumeferential speed of the feed roller, above values *f* are essentially decreased, this leading to roller slipping relative to the wire. This phenomenon, as follows from the oscillograms, may be of self-oscillating nature in the range of impact of each pulse, changing its parameters. The oscillogram (Figure 4, *c*) was produced for the case, when a regulator of the clamping force was mounted in the feed system. At pulse action a certain movement of the hose holder shank starts simultaneously with wire movement at increase of clamping force. Due to different inertia properties of the wire in the hose holder guide, the wire continues moving through the guide, and the holder stays in place. Application of the regulator leads to less slipping and to distortion of the shape of the output pulse — more significant than is usually found in the case of wire moving through the guide [8]. The above phenomenon should be taken into account in setting up the pulse feed mechanism.

Oscillograms in Figure 4, *b, d* were taken for the case of application of feed rollers with a groove along the roller generatrix. The oscillogram (Figure 4, *d*) presents the result of operation of the pulsed feed mechanism without application of the regulator, and Figure 4, *b* — with the regulator. In both the cases the shape of output pulse is acceptable for action on the technological process. The difference consists in that the regulator also somewhat distorts the shape of the feed pulse.

Problem 2. *Elimination or lowering of vibrations in the mechanisms of pulsed wire feed with increase of reliability of the mechanism proper and the semi-automatic machine, as a whole.*

Solution of this problem is of special interest, as successful broad introduction of mechanized arc welding equipment with a pulsed wire feed depends on how effectively will the vibrations be reduced, and how close its operation is to that of regular feed mecha-

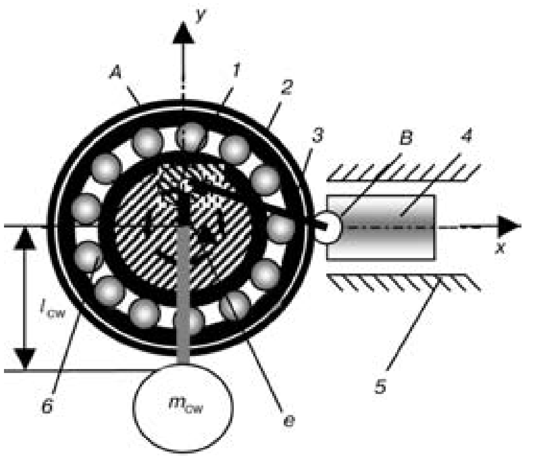

Figure 5. Mechanism of pulsed feed with one moving grip: *1* — eccentric axis; *2* — outer mandrel for fastening hinge *B* of the grip *4*; *3* — outer race of bearing; *5* — guides; *6* — electric motor shaft (*A* — conditional hinge between crank and connecting rod)

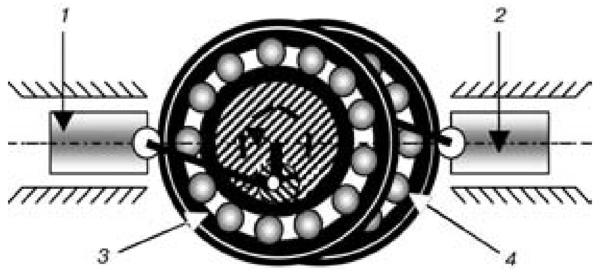

Figure 6. Mechanism of pulsed feed with two moving one-sided grips (*1, 2*); eccentric mechanisms (*3, 4*) are conditionally shifted relative to each other for better presentation

nisms in terms of the characteristics of reliability and sanitary-hygienic norms.

Higher level of vibrations for electrically-driven mechanisms with a pulsed wire feed, as shown by investigations, is felt particularly at frequencies above 20 Hz, i.e. in the frequency range, required for welding. Technical solutions, associated with application of vibration-insulating devices (springs, elastic gaskets, etc.), are effective in a narrow frequency range. Use of systems of mechanism balancing should be more effective in this case.

Practically any mechanism with a pulsed feed, driven by an electric motor, uses a device for motion conversion, which is based on a crank pair as one of the simplest and most effective mechanisms. This integrated solution allows the problem to be formalized, and a common approach to be developed to design solution for lowering the vibrations in the pulsed feed mechanisms.

In mathematical terms [9], the conditions for balancing any mechanism have the following form:

$$x_s = \text{const}; \quad y_s = \text{const}; \tag{5}$$

$$J_{xz} = \text{const}; \quad J_{yz} = \text{const}, \tag{6}$$

where x_s, y_s are the co-ordinates of a common centre of moving masses; J_{xz}, J_{yz} are the moments of inertia of the links.

From equations (5) and (6) it follows, that the main, and, as shown by experience, most complicated task of calculation of balancing of actual mechanisms, is determination of the masses of units and their co-ordinates. For mechanisms with a pulsed wire feed with one-sided grips, the simplest in terms of design is a device with a bearing, mounted eccentrically on the electric motor shaft. In this case, the outer race of the bearing is hinged to the moving one-sided grip, as in Figure 5, which does not show the second locking grip. The system is a crankshaft, formed by a section between the centres of bearing and eccentric shaft (hinge A), as well as a connecting rod in the form of a section between two hinges A, B and the slide, formed by one-sided grip with the wire, moved by it (not shown in the Figure). In this system, the connecting rod is a certain formation without any real frame, and, therefore, also it has mass $m_{\text{c.r}} = 0$. Crank mass m_{c} will consist of that of the bearing with elements attached to it. The device may be considered as eccentric mechanism, and just the rotating masses may be balanced.

In keeping with [9], let us perform the balancing, by mounting on the line, passing through the center of gravity of the mechanism, on the other side of the axis of rotation, a counterweight of mass m_{cw}, determined in view of expressions (5) and (6):

$$m_{\text{cw}} = m_{\text{c}} e / l_{\text{cw}}, \tag{7}$$

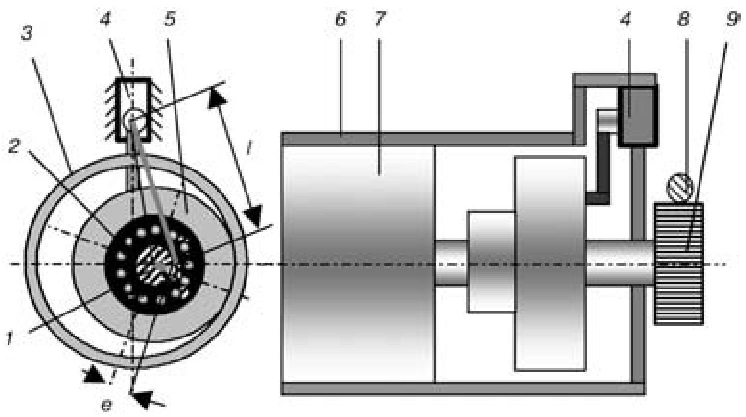

Figure 7. Schematic representation of the mechanism of electrode wire pulsed feed with QWC: *1* — eccentric shaft; *2* — bearing; *3* — gear with internal toothing; *4* — motion pulse former; *5* — gear with external toothing; *6* — case; *7* — drive electric motor; *8* — electrode wire; *9* — feed roller

where e is the eccentricity; l_{cw} is the distance of counterweight attachment from center of gravity O.

From relationship (7) it follows, that when taking a decision on mounting the counterweight, it is necessary to select either its mass, or distance from the mechanism center of gravity. In this case, it is convenient to use a counterweight in the form of a disc with the mass, close to that of the motion converter, which is mounted at a short adjustable distance from the center of mass in the direction, opposite to that of the eccentric.

A design with two grips moving towards each other is often used, when designing pulsed feed mechanisms. Such an algorithm of mechanism operation solves the problem of its balancing by two symmetrical feed systems (Figure 6). With two oppositely-placed grips and eccentric converters of motion, the mechanism design is functionally perfect.

In pulsed feed mechanisms with quasi-wave converters (QWC) [4], one of the variants of which is shown in Figure 7, the balancing problem is significantly more difficult to solve, which is caused by double application of forces in the kinematic links of the mechanism: transfer of the force from eccentrically mounted and moving gear with external toothing *5* to gear *3* with internal toothing and further to feed roller *9* with electrode wire *8*. Moreover, forces are applied, which control the motion of gear *4* in the device, forming the motion pulse. Formalizing the kinematic structure of the mechanism, two crank systems can be singled out. It is practically impossible to study such a mechanism in terms of balancing, taking into account all the kinematic links, which is not something really required, as the main unbalanced mass in this case, similar to the previous one, is made up by mechanism elements, rotating on the eccentric, namely bearing *2*, gear with external toothing *5*, and eccentric shaft *1*. Therefore, the above procedure for balancing with the counterweight according to expression (6) is also applicable here. Unfortunately, it has not so far been possible to find a functionally justified engineering solution with oppositely-mounted eccentrics for a design with QWC in the general case. An exception in this case is the mechanism with an additional motion converter (secondary eccentric), described in [10]. In development and design in the general case we used regular disc counterweights, mounted on opposite eccentricities, which provided a 3 to 4 times lowering of vibrations, transferred to the case.

CONCLUSIONS

1. The ability has been established to lower the probability of slipping of feed rollers relative to electrode wire at pulsed feed, due to changing the friction characteristics in the contact zone by selection of the shape and structure of feed surface of rollers or creating optimal conditions for clamping of feed rollers to electrode wire.

2. As vibrations of an electrically-driven mechanism of pulsed feed of electrode wire of any design result from operation of the device for conversion of the rotary motion into pulsed-translational motion or pulsed-rotary motion, it is established that the most simple, accessible and effective method to reduce them is static balancing of just the rotating masses, complemented by use of vibration-absorbing devices.

1. Voropaj, N.M., Saveliev, O.N., Semergeev, S.S. (1980) Electromagnetic mechanisms of pulsed electrode wire feed. *Avtomatich. Svarka*, **1**, 46–49.
2. Dudko, D.A., Chvertko, A.I., Svyatsky, E.M. et al. *Mechanism for welding wire feed*. USSR author's cert. 703266. Int. Cl. B 23K 9/12. Publ. 15.12.79.
3. Lebedev, V.A., Nikitenko, V.P. (1984) Grips for pulsed electrode wire feed. *Avtomatich. Svarka*, **10**, 52–58.
4. Lebedev, V.A., Moshkin, V.F., Pichak, V.G. (1996) New mechanisms for pulsed electrode wire feed. *Ibid*., **5**, 39–44.
5. Voropaj, N.M. (1996) Parameters and technological means of arc welding with pulsed feed of electrode and filler wire. *Ibid*., **10**, 3–9.
6. Belfor, M.G., Paton, V.E. (1974) *Equipment for arc and slag welding and surfacing*. Moscow: Vysshaya Shkola.
7. Lebedev, V.A., Svetnikov, B.G. (1984) Evaluation of the influence of guide and current conduit nozzle bends on resistance to electrode wire movement (Elements of static analysis). *Avtomatich. Svarka*, **9**, 35–37.
8. Lebedev, V.A. (1999) Influence of guide channel of semi-automatic welding machine on the parameters of pulsed electrode wire feed. *Ibid*., **2**, 45–48.
9. Shepetilnikov, V.A. (1982) *Balancing of mechanisms*. Moscow: Mashinostroenie.
10. Lebedev, V.A., Pichak, V.G., Smolyarko, V.B. (2001) Pulsed wire feed mechanisms with pulse parameter control. *The Paton Welding J.*, **5**, 27–33.

FLUX-CORED WIRES WITH METAL CORE FOR GAS-SHIELDED WELDING

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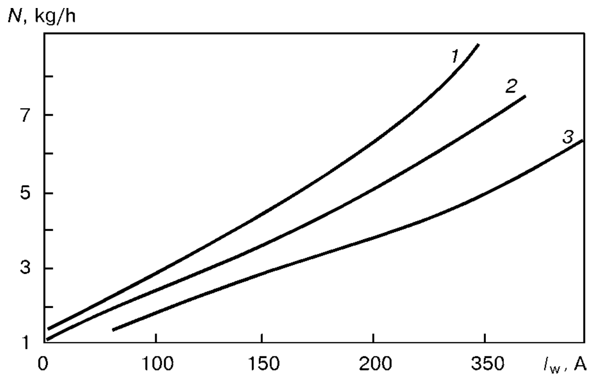
Considered are the issues associated with development of new flux-cored wires with a metal core, combining high deposition efficiency and high yield of the deposited metal. The use of a thick-walled sheath provides excellent feed of the wire.

Key words: *arc welding, flux-cored wire, metal core*

Welding using flux-cored wires is widely applied in many fields of engineering and construction owing to a high productivity of the process and the possibility of regulating properties of a welded joint, as well as operational-welding characteristics, through introducing minor additions of materials to the wire core. One of the modifications of such wires which have gained wide acceptance lately is wire with a metal powder core intended for gas-shielded welding. This wire combines high deposition efficiency and high yield of the deposited metal (95–96 %), which is characteristic of welding using solid wire.

Flux-cored wire with a metal core forms slag islands on the weld surface during melting. However, unlike welding with a solid wire, these slag crusts can be readily removed from the surface. The welding process using wires with a metal core is characterised by stability and minimum spattering losses. The favourable shape of the welds and deep penetration provided by these wires make them the wires of choice for robotic and automatic welding. Welding using wire with a metal core is performed in the atmosphere of shielding gases (CO_2 or Ar-based mixtures).

The E.O. Paton Electric Welding Institute is active in development of flux-cored wires with a metal core for CO_2 welding and welding in the Ar + CO_2 mixture. The wires developed have a thick metal sheath, which causes no problems with feed of such a wire in the case of mechanised welding. A small amount of non-metallic materials in the core is used to improve characteristics of stability of the arc discharge and regulation of metallurgical and technological properties of slag.



Deposition efficiency N in the case of using flux-cored wires and solid wires with a diameter of 1.2 mm for mechanised welding: *1* — flux-cored wire with metal core; *2* — same with rutile core; *3* — solid wire

The basic flux-cored wire of the PP-AN70M grade, having a diameter of 1.2 (1.4, 1.6) mm, is intended for CO_2 welding or welding in the Ar + CO_2 mixture. The 1.4 and 1.6 mm wires are designed for welding mostly in the flat position. During melting, they form slag islands of the type close to rutile on the weld surface. The main system of metal alloying is Si–Mn. Welding in the Ar + CO_2 mixture provides better characteristics of ignition of the arc and stability of its burning. Multilayer welded joints can be produced without removal of slag islands from the surface of the preceding layers.

Flux-cored wire of the PP-AN72M grade, having a diameter of 1.2 mm, is intended for welding in a mixture of gases of low-alloy steels with increased requirements for tough-ductile properties at low temperatures. The system of metal alloying is Si–Mn–Ni. The wire provides quality welding of joints in thick sections of metal at a welding current of 250–350 A.

Table 1. Chemical composition of deposited metal

Wire grade	*Shielding gas*	*Content of elements, wt.%*					
		C	*Mn*	*Si*	*Ni*	*S*	*P*
PP-AN70M	CO_2	0.07	1.35	0.55	–	0.012	0.015
Same	Ar + CO_2	0.07	1.45	0.60	–	0.011	0.016
PP-AN72M	Same	0.06	1.442	0.45	1.46	0.012	0.015

Table 2. Typical mechanical properties of weld metal and welded joints

Wire grade	*Shielding gas*	*Tensile tests*			*Impact bending tests*	
		σ_y, *MPa*	σ_t, *MPa*	δ, %	T_{test}, °C	*KCV*, J/cm^2
PP-AN70M	CO_2	525	600	26	−20	110
Same	Ar + CO_2	530	610	28	−20	120
PP-AN72M	Same	535	605	29	−40	95

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Welding downward on a vertical plane can be successfully performed at lower values of the welding current.

Welding using flux-cored wires with a metal core, owing to the use of thick-walled sheath, provides excellent feed of a wire, not inferior to that of a solid wire.

Chemical composition of the deposited metal and mechanical properties of the weld metal and welded joints are given in Tables 1 and 2.

The diffusible hydrogen content is 3–5 cm^3 per 100 g of the deposited metal. Porosity resistance is high.

Pilot sample of the wire with a metal core has been developed. This wire allows welding of thin metal (1–3 mm), as well as making of root welds without backing.

Comparing indicators of the process productivity using wires for mechanised welding shows (Figure) that flux-cored wires and wires with a metal core, owing to a high current density, make it possible to achieve higher values than solid wires. Wires with a metal core provide deep penetration of the base metal and high productivity of the process. They can be used for robotic welding.

INSTALLATION FOR MAGNETRON SPUTTERING OF COATINGS ON GLASS PANELS

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The paper deals with an all-purpose unit for magnetron sputtering for applying the reflecting and other kinds of coatings on sheet materials.

Key words: *coating application, magnetron sputtering, reflecting coating, glass panels, cyclic-action unit, vacuum chamber*

One of the practical applications of vacuum coatings technologies is application of an aluminium coating on glass to produce a reflecting layer on mirrors. Traditional technologies of such coatings application include aluminium evaporation in vacuum (0.01 Pa), using resistance heating. In the CIS this technology is implemented, using UVN-15 and UV-18 units, developed in SKB VP (Riga, Latvia), and manufactured by «Vacuummash» (Kazan, Russia). It, however, has a significant drawback, related to aluminium interaction with the evaporator material (tungsten). Intermetallic inclusions may lead to dimming of the reflecting layer and its delamination already after 1.5–2 months of service. In this connection, just 15–20 % of products, produced in these units, meet the requirements of GOST 17716–91 to reflecting properties of the spray-deposited layer [1]. In addition, this equipment has been developed more than 20 years ago, and is quite obsolete.

Method of magnetron sputtering has become intensively developed lately, which offers considerable advantages in terms of the coating quality and their deposition rate. It provides a high adhesion of the deposited coatings, absence of the drop phase, preservation of the stoichiometry of the sprayed material at deposition rates of several micrometers per minute. The method is used in the developed flow lines for deposition of the reflecting aluminium coating on glass panels for production of household mirrors. The lines consist of 5–7 chambers, covering the entire operational sequence, including surface preparation and coating deposition (including the ability to apply adhesion underlayer and multilayer working coating), with a high level of automation of the entire process [2]. Such equipment is designed for mass-production of items with reflecting coatings in large volumes.

However, use of such lines under the conditions of small enterprises is difficult, in view of their high cost and considerable dimensions, as well as for the reason of such enterprises having to quickly react to customer requirements with manufacturing of small batches of specialized products. For this reason, the PWI developed a cyclic-operation magnetron sputtering unit UMR-15-2 for coating deposition on sheet materials and, primarily, for application of reflecting coatings on glass panels to make household mirrors.

Cyclic-operation units UMR-15-2 consist of a cylindrical working chamber of 7 m^3 volume; a system

Magnetron sputtering unit UMR-15-2

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of high-vacuum diffusion pumps; two-line system of roughing-down; system of control and monitoring of the plants with a remote control panel; system of monitoring the vacuum condition of elements; system of feeding and dosing the gas components; module of group system of magnetron sputtering; power source of magnetron sputtering system; load module with transportation system for displacement of items inside the chamber; transportation system of displacement of the sputtering device module; outer element of transportation system of the load module.

Vacuum chamber is sealed off with an electrically-driven mobile cover and a pneumatic clamping system. Transportation system of the sputtering device is located below along the generatrix of the chamber cylinder, running horizontally. The group sputtering module proper is made up of two sputtering devices and mounted vertically on the transportation system carriage, providing reciprocal motion of the module along the entire length of the chamber. Item blanks are placed on each side of the transportation system of sputtering module, in our case this is sheet glass (substrate) (Figure). Moving between the substrate planes the sputtering module ensures simultaneous processing of the surfaces of both the substrates. To provide the uniformity of coating over the entire area of two substrates, facing the module, the magnetic systems of sputtering devices are transformed so, that the erosion zones, formed by the loop of discharge in cathode sputtering, simulated two linear sputtering sources, each turned to its «own» substrate, respectively. Implementation of such a schematic of the sputtering device allows doubling the area of items, processed by the sputtering module in one pass. Group sputtering module, made up in this case of two sputtering devices with separate power supply, provides the ability of conducting the operations of ion processing, application of the adhesive underlayer (if required), application of the functional and protective coating as a continuous sequence. Design of the magnetrons allows conducting a fast replacement of sputtering target (20–30 min).

Application of loading module with its own transportation system of items displacement allowed increasing the number of loaded substrates and, thus, increasing the coefficient of utilization of the chamber working volume. For batch-operation units this value is the ratio of total area of metallized surfaces of substrates to volume of working chamber:

$$K_{ut} = S_s N / V_{ch},$$

where S_s is the area of substrate metallizing; N is the number of substrates; V_{ch} is the volume of the working chamber.

For UMR-15-2 at maximum load K_{ut} = 4.7 (for UVM-15 K_{ut} = 2.6).

Unit specification

Efficiency per shift, m^2	65
Operating mode	three-shift
Coating thickness, μm	0.01–0.50
Number of service personnel, pers.	3
Maximum size of substrates, m	2.5×1.5
Overall dimensions, m	3.5×4.5×2.5

UMR-15-2 unit may be used by enterprises, oriented to metallizing of sheet items of glass, ceramics and plastic, but primarily to producing a reflective coating on glass panels in fabrication of household and decorative glasses.

Although the unit is mainly designed for applying the reflective coating on glass panels, it, however, offers basic capabilities of producing such coatings of non-magnetic materials and alloys and implementation of the mode of reactive spraying for application of coatings from oxides, nitrides etc., using plastics and ceramics as substrates.

1. Serdyuk, V.I., Gnatyuk, O.V. (2001) Improvement of methods for increasing quality of vacuum coatings. *The Paton Welding J.*, **8**, 53–54.
2. Danilin, B.S. (1989) *Application of low-temperature plasma in thin film deposition*. Moscow: Energoatomizdat.

Developed at the PWI

PROCESS OF CONSUMABLE-ELECTRODE WELDING WITH PROGRAMMABLE CHANGE OF GAS SHIELDING AND WELDING CURRENT MODULATION

Pulsed-arc welding with programmable feed of shielding gases into the zone of the arc allows solving the problems of control of the processes, proceeding at the electrode tip, in the arc and the weld pool. Developed equipment for automatic and mechanized welding includes a specialized power source, block of modulation of various shielding gases with different physical-chemical properties and a device for synchronizing the current flowing through the arc with the kind of shielding gas. The above system allows making joints of various types of steels of small, medium and great thickness at the current of 80–300 A.

Application of the new welding process allows improving the energy and technological characteristics of the arc, expanding the capabilities of mechanized welding processes, saving welding consumables and power. New technology, compared to the traditional ones (welding in CO_2, Ar-based mixtures, pulsed-arc welding in Ar + CO_2 mixture), has the following advantages:

- improvement of mechanical properties, in particular impact toughness, at below zero temperatures by 30 %;
- reduction of argon flow rate by 2.5–3 times;
- improvement of weld appearance;
- ability to control the depth and shape of penetration;
- decreasing spatter by 30 %;
- conducting high-quality gravity position welding of sheet metal.

The above advantages of the new process of consumable-electrode welding allow development of highly effective and cost-saving technologies of welding thin metal structures, as well as multipass welding of metal structures of medium and great thickness.

Automatic and mechanized consumable-electrode welding and surfacing of low-carbon, low-alloyed structural steels, and Al-based alloys can be used in shipbuilding, chemical, petrochemical and food mechanical engineering.

The developed welding process (B.E. Paton, V.K. Lebedev, P.P. Shejko, A.M. Zhernosekov, S.A. Shevchuk) is protected a patent of Ukraine for invention No.43424.

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