International Scientific-Technical and Production Journal

The Paton WELDING JOURNAL

December 2010 # 12

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

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

Publisher: *International Association «Welding»*

Address:
E.O. Paton Electric Welding Institute,
International Association «Welding»,
11, Bozhenko str., 03680, Kyiv, Ukraine
Tel.: (38044) 287 67 57, 200 82 77
Fax: (38044) 528 04 86, 200 82 77
E-mail: journal@paton.kiev.ua
http://www.nas.gov.ua/pwj

State Registration Certificate
KV 4790 of 09.01.2001

Subscriptions:
$324, 12 issues per year,
postage and packaging included.
Back issues available.

CONTENTS

PECULIARITIES OF THERMAL AND HYDRODYNAMIC PROCESSES OCCURRING IN TIG AND A-TIG WELDING OF STAINLESS STEEL

D.V. KOVALENKO, I.V. KRIVTSUN, V.F. DEMCHENKO and **I.V. KOVALENKO**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Analysis of distribution of temperature over the surface of the weld pool in TIG and A-TIG welding of stainless steel using the stationary and moving arc was carried out on the basis of calculation and experimental data. It is shown that in TIG and A-TIG welding the distribution of temperature over the weld pool surface above the boiling point has a characteristic plateau, the size of which is commensurable with size of the anode spot of the arc, the maximal temperature and size of this plateau being somewhat smaller in A-TIG welding. Problems of mathematical description and modelling of the Marangoni convection developing in A-TIG welding by the thermal-capillary and concentration-capillary mechanisms are discussed. Two circulation flows may form in the weld pool, their interaction causing a flow of the melt directed deep into the weld pool.

Keywords: *TIG and A-TIG welding, stainless steel, stationary and moving arc, weld pool surface temperature, capillary Marangoni convection, force factors, penetration, experiment, mathematical modelling*

The authors in their previous studies [1, 2] considered the phenomenological model of existence and interaction of the TIG/A-TIG arc–weld pool system, as well as the probability of existence of the quasi-keyhole in A-TIG welding. Peculiarities of the effect on formation of the weld pool and weld by thermal, mass exchange, electromagnetic, hydro- and gas-dynamic processes occurring in the arc column and weld pool in A-TIG welding using the stationary and moving arc were studied on the basis of analysis of experimental data and theoretical estimates. A substantial, fundamental difference in formation of the welds made by TIG and A-TIG welding with the moving and stationary arc was shown. This difference consists in the fact that in welding with the moving arc the processes of melting and solidification of the weld metal occur simultaneously, whereas in spot welding they are separated in time. Formation of the A-TIG spot weld is characterised by the presence of a specific deep crater with reinforcement on the weld periphery, which results from subsequent shrinkage phenomena. A fundamentally different formation of flows of the arc column plasma about the weld pool surface, directed from the periphery to centre, may take place in A-TIG welding, compared to TIG welding, this causing transfer of the overheated metal to the pool bottom and formation of the narrow and deep welds.

Study [3] offered a conjugate mathematical model of thermal, electromagnetic and hydrodynamic processes occurring in a weldment in stationary (spot) TIG welding. As established by modelling, parameters that determine the thermal state and hydrodynamics of the weld pool in arc welding are sizes of the anode (diameter of the current channel at anode) and heat spots of the arc, R_a and R_h, respectively. The cardinal difference in penetrating capacity of the TIG and A-TIG welding methods is caused by a different proportion between sizes of the current and heat spots. Comparative analysis of the effect by three different force factors (Lorentz force, Marangoni effect, and Archimedes force) on the hydrodynamics and thermal state of the weld pool was carried out on the basis of results of experimental and calculation studies of the kinetics of penetration in TIG and A-TIG welding. At a small size of the anode spot (less than 4 mm), the dominant factor that determines depth and shape of the weld spot was shown to be a centripetal component of the Lorentz force.

Analysis of our results, as well as results of the studies performed by other authors, required additional experimental and theoretical investigations.

The purpose of this study was to conduct comparative analysis of experimental and calculation data on distribution of temperature over the weld pool surface, and consider peculiarities of capillary convection in TIG and A-TIG welding of stainless steel by using the stationary and moving arc.

Peculiarities of distribution of temperature over the weld pool surface. The calculations made by using the mathematical model [3] indicate to the probability of increase in density of the heat flow that exists at certain sizes of the anode and heat spots of the stationary TIG arc in welding of stainless steel 304, while this increase may lead to extra overheating of the weld pool surface to a temperature above boiling point T_b. This results in growth of heat losses for evaporation and decrease in assimilation of heat by the weldment. The temperature profile in overheating of the weld pool surface (in transverse direction) to a temperature above the boiling point has a characteristic plateau at $T > T_b$ (Figure 1).

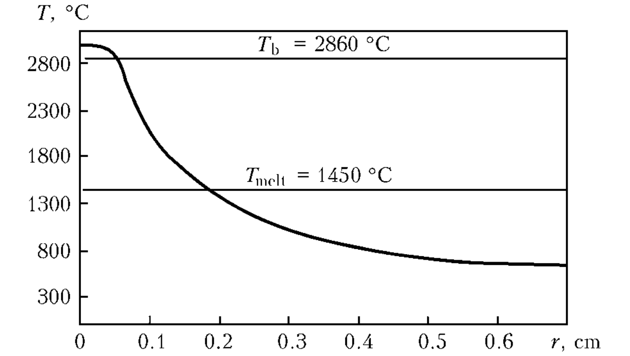


Figure 1. Calculated values of distribution of temperature over the weld pool surface in transverse direction at R_a = 1.25 mm and R_h = = 1.5 mm: T_{melt} — melting temperature

An experiment on determination of the distribution of temperature over the surface of the weld pool along its axis was carried out to check the modelling calculation results. TIG and A-TIG welding with the moving arc was performed on a 5 mm thick specimen of stainless steel 304. Aerosol activating flux PATIG S-A was used for A-TIG welding. Welding conditions were similar to the calculated ones: welding current — 100 A, installed arc length — 1.5 mm, and welding speed — 100 mm/min. The tungsten electrode employed contained 2 % ThO_2, and had a diameter of 3.2 mm and sharpening angle of 35°. Argon was used as a shielding gas (flow rate — 12 l/min).

Appearance of the experimental setup is shown in Figure 2. «Raytek» computerised infrared pyrometer Marathon MM 1MH was used as a measuring device. Specifications of the pyrometer were as follows: range of temperatures measured — 650–3000 °C, spectral range — 1 μm, error — ±0.3 % or ±1 °C, time of reaction — 1 ms, and measurement point diameter — 1 mm.

The fixed pyrometer was focused onto a point marked on the weld axis on the surface of a specimen welded. The weld pool formed by the arc moved through the marked point during welding. Simultaneously, the temperature on the surface of the weld pool was measured along its longitudinal axis. Schematic of the experiment is shown in Figure 3.

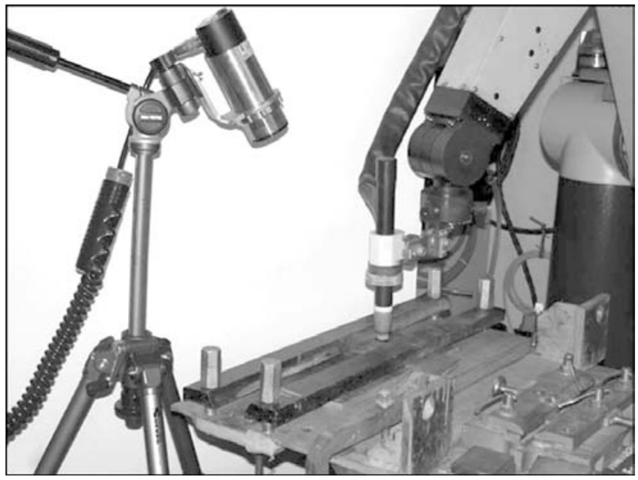


Figure 2. Appearance of experimental setup

Results of the experimental studies are shown in Figure 4. In TIG and A-TIG welding with the moving arc the distribution of temperature over the weld pool surface above the boiling point has a characteristic plateau, the size of which is commensurable with that of the anode spot of the arc [4]. Diameter of this plateau for TIG and A-TIG welding is 1.75 and 1.5 mm, respectively. However, the maximal temperature of the plateau is somewhat lower in A-TIG welding (2600 °C), compared to TIG welding (2650 °C). Also, a somewhat increased level of temperature is observed in the tailing part of the weld pool in A-TIG welding.

It should be noted that the presence of this overheating plateau proved the probability of existence of the quasi-keyhole in A-TIG welding [1].

Role of hydrodynamic processes and peculiarities of capillary convection in metal penetration. One of the force factors affecting the hydrodynamics of the melt is Lorentz force, which is axisymmetric in the case of spot TIG and A-TIG welding, i.e. $\vec{F} = \vec{F}(r, z)$, where r and z are the radial and axial coordinates. The calculation data obtained in study [3] indicate that at a certain proportion of sizes of the anode and heat spots of the arc, and at anode spot radius R_a < 4 mm, which are characteristic of A-TIG welding, the dominant force factor that determines

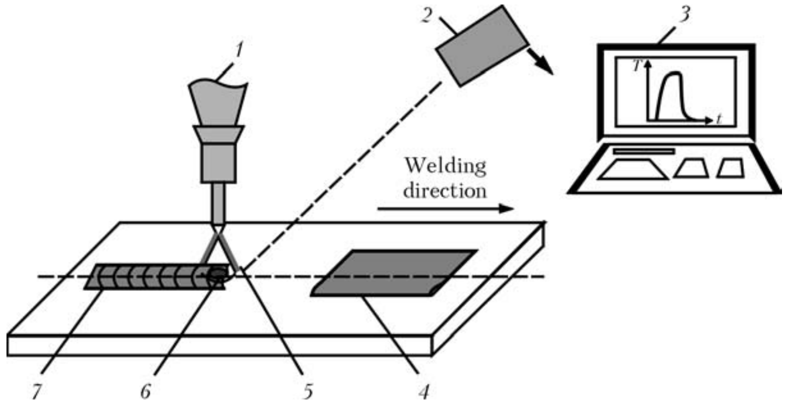


Figure 3. Schematic of experiment: *1* — torch; *2* — pyrometer; *3* — computer system with software; *4* — activator; *5* — arc; *6* — weld pool; *7* — weld

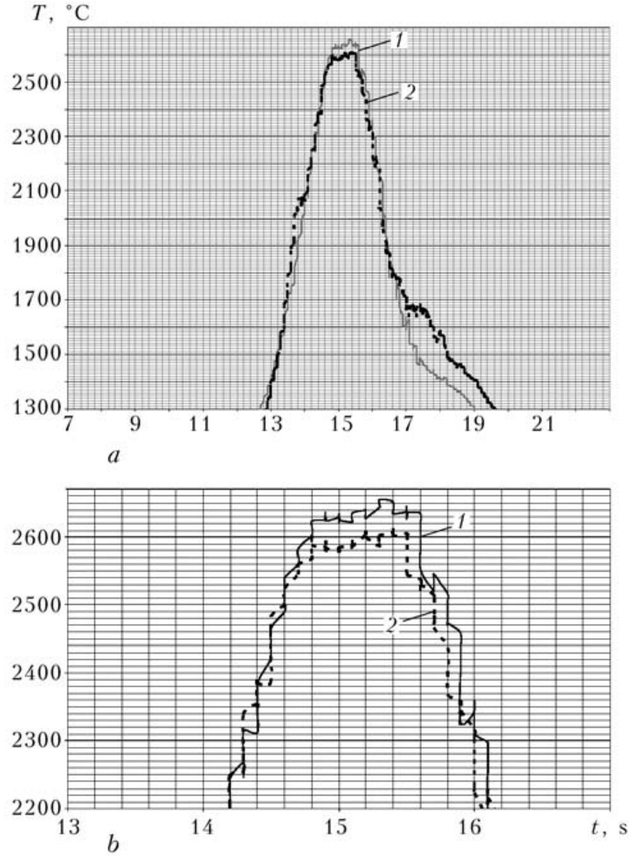


Figure 4. Experimental curves of distribution of temperature over the weld pool surface in longitudinal direction depending on welding time in temperature ranges of 1300–2800 (*a*) and 2200–2800 (*b*) °C: *1* — TIG welding; *2* — A-TIG welding

the hydrodynamics of the weld pool is a radial component of the Lorentz force, which is centripetal at the axisymmetric magnetic field. It should be noted that for the weld pool surface this force in the anode spot is directly proportional to squared welding current I^2 and inversely proportional to cubic anode spot radius R_a^3 [1, 2]:

$$\vec{F}_{rot}(r, 0) = -\mu_0 \frac{I^2}{4\pi R_a^3} \frac{r}{R_a} \vec{e_r}, \quad 0 < r < R_a,$$

where μ_0 is the relative magnetic permeability, and $\vec{e_r}$ is the unit radius vector.

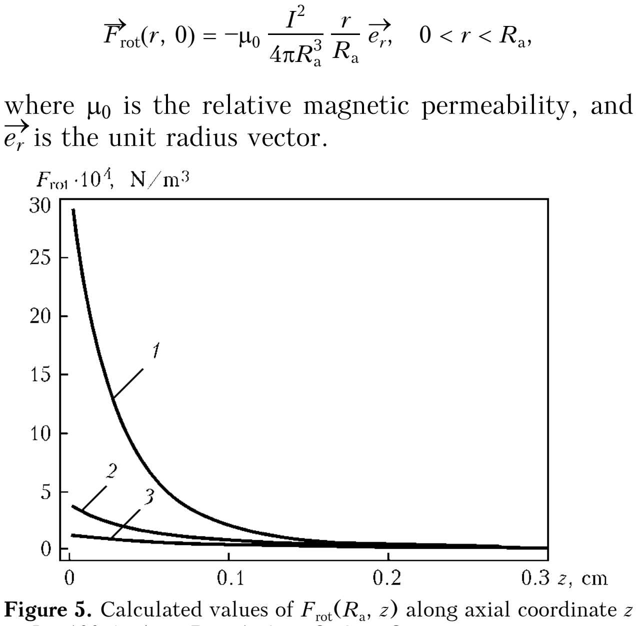


Figure 5. Calculated values of $F_{rot}(R_a, z)$ along axial coordinate z at I = 100 A: *1* — R_a = 1; *2* — 2; *3* — 3 mm

The effect of the size of the anode spot on the centripetal component of the Lorentz force is shown in Figure 5.

The vortex flow of the melt forms in the weld pool under the effect of the centripetal component of this force. Near the free surface this flow is directed from the periphery toward the weld pool centre. The molten metal flows moving from the opposite directions turn in the axial part of the pool to the axial direction, transporting the metal overheated to the boiling point or higher (see Figures 1 and 4) from the centre of the heat spot toward the pool bottom. As the speeds of movement of the molten metal are kept at a sufficiently high level (max $|\vec{V}| \approx 50$ cm/s), the moving melt retains much of overheat, thus leading to densification of temperature with a high temperature gradient in the weld pool near the melting front. This creates conditions for increase in the penetration depth.

Consider the effect of capillary convection (Marangoni effect) on penetrating power of the arc in A-TIG welding. It is a known fact that surface-active elements influence the surface tension coefficient of metal. Oxygen, sulphur, fluorine etc. may serve as surface-active elements that get from the flux to the melt in A-TIG welding. For example, as established in study [5], surface tension coefficient γ as a function of oxygen content C in steel grows with decrease in the oxygen concentration ($\beta_C = \partial\gamma/\partial C < 0$). As the oxygen concentration on the weld pool surface decreases with increase in temperature, $\partial C/\partial r > 0$ and, hence, $\beta_C\ \partial C/\partial r < 0$. This is indicative of the probability of formation of the reverse concentration-capillary Marangoni convection caused by the oxygen concentration gradient on the free surface of the weld pool.

At the same time, according to the data of study [6], temperature surface tension coefficient $\beta_T = \partial\sigma/\partial T$ of the iron melt with an oxygen content of $(150–350)\cdot10^{-6}$ takes a positive value within a temperature range of 1873–2123 K. Hence, $\beta_T \frac{\partial T}{\partial r} < 0$, this being indicative of the probability of the direct thermal-capillary convection. If the concentration-capillary and thermal-capillary convections combine, the condition of balance of tangential stresses on the free surface of the melt can be written down as

$$v \frac{\partial V_r}{\partial z}\Big|_{z=0} = -\frac{1}{\rho}\left[\beta_T \frac{\partial T}{\partial r} + \beta_C \frac{\partial C}{\partial r}\right].$$

Therefore, A-TIG welding features the probability in principle of formation of the reverse (from the periphery of the pool toward its centre) Marangoni flow caused by both thermal-capillary and concentration-capillary mechanisms. To experimentally determine β_T and β_C, it is extremely important to provide the necessary conditions for finding partial derivatives

$\partial\sigma/\partial C$ and $\partial\sigma/\partial T$. Otherwise the experimental data may be noisy.

High-temperature heating of metal up to the boiling point, $T = T_b$, takes place in the central part of the weld pool surface in the overheating plateau region. As follows from physical considerations, $\gamma(T, C) \to 0$ at $T \to T_b$, independently of the oxygen content. This means that

$$\partial\sigma/\partial r = \beta_T \frac{\partial T}{\partial r} + \beta_C \frac{\partial C}{\partial r} > 0$$

within a certain temperature range ($T_{ext} < T < T_b$, where T_{ext} is the extreme temperature) below the boiling point, i.e. the surface tension coefficient at certain definite temperature $T = T_{ext}$ has a maximum, and direction of the surface force in this temperature range corresponds to the direct (from the centre to periphery of the pool) capillary convection. Therefore, the opposite, as well as direct (from the centre to periphery of the weld pool at $T \in [T_{ext}, T_b)$ and reverse (from the periphery of the weld pool to its centre at $T < T_{ext}$) capillary convections may simultaneously exist on the weld pool surface in A-TIG welding. In this case, two vortexes may form in the weld pool, the interaction of which results in the flow of the melt directed deep into the weld pool.

It should be noted in conclusion that, in our opinion, the available experimental data on dependencies $\beta_C = \beta_C(T, C)$ and $\beta_T = \beta_T(T, C)$ within a wide temperature range are insufficient to theoretically estimate with certainty the effect by the Marangoni convection on the penetrating capacity of A-TIG welding. Investigation of this effect requires additional experimental studies of the dependence of the surface tension coefficient on the temperature and concentration of an activating element in the melt, especially for the conditions of interaction of the flux layer with the weld pool surface.

1. Paton, B.E., Yushchenko, K.A., Kovalenko, D.V. et al. (2006) Role of quasi-keyhole and Marangoni convection in formation of deep penetration in A-TIG welding of stainless steel (Phenomenological model of A-TIG welding of stainless steel). In: *Proc. of Joint 16th Int. Conf. on Computer Technology in Welding and Manufacturing and 3rd Int. Conf. on Mathematical Modelling and Information Technologies in Welding and Related Processes* (Kiev, Ukraine, June 2006). Kiev: PWI, 258–263.
2. Yushchenko, K.A., Kovalenko, D.V., Kovalenko. I.V. et al. (2007) Phenomenological model of existence and interaction of the system of activated arc and liquid channel of metal pool in A-TIG welding. *IIW Doc. XII-212-1112–07*.
3. Yushchenko, K.A., Kovalenko, D.V., Krivtsun, I.V. et al. (2008) Experimental studies and mathematical modelling of penetration in TIG and A-TIG stationary arc welding of stainless steel. *IIW Doc. XII-212-1117–08*.
4. Yushchenko, K.A., Kovalenko, D.V., Kovalenko, I.V. (2003) Investigation of peculiarities of A-TIG welding of stainless steels. *IIW Doc. 212-1047–03*.
5. Lancaster, J.F., Mills, K.C. (1991) Recommendations for the avoidance of variable penetration in gas tungsten arc welding. *IIW Doc. 212-796–91*.
6. Taimatsu, M., Nogi, K., Ogino, K.J. (1992) Surface tension of liquid Fe–O alloy. *High Temp., Soc. Jap.*, 18(**1**), 14–19.

RISK OF FORMATION OF CARBIDES AND α-PHASE IN WELDING OF HIGH-ALLOY CHROME-NICKEL STEELS

V.I. MAKHNENKO[1], **S.S. KOZLITINA**[1], **L.I. DZYUBAK**[1] and **V.P. KRAVETS**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]Rivnenskaya NPP, Kuznetsovsk, Ukraine

The possibility is considered of using calculation methods to predict the risk of formation of the σ-phase in the HAZ metal of chrome-nickel steels at a carbon content of about 0.08 % and higher. It is shown that the use of temperature-time constitutional diagrams for steel of a corresponding composition, combined with temperature cycles at points in the HAZ metal, allows predicting the degree of sensitization of the corresponding HAZ region under different welding conditions.

Keywords: *arc welding, chrome-nickel steels, welded joints, sensitization, σ-phase, intergranular cracks, stress corrosion, temperature-time diagram*

Problem of formation of the third phases is one of the fundamental in welding of austenite chrome-nickel steels with increased content of carbon. Corresponding recommendations were developed for its solving and included in many reference books [1 and others]. It is characteristic that mentioned third phases (besides initial austenite and ferrite) appear after a primary crystallization during some soaking at specified temperature interval (Figure 1). They made no serious problems for the near-weld zone metal in a single run welding. An overlay of the curves of thermal cycles for specific points of the near-weld zone on respective temperature-time diagrams (*c*-curves) for steel of a corresponding composition (Figure 2) in multi run welding, however, shows that the accumulation of conditions for formation of the chromium carbides along the grain boundaries (due to diffusion of carbon controlled by *c*-curve in Figure 2, *a*) or σ-phase accumulation due to δ-ferrite decay and formation of complex intermetallics (Figure 2, *b*), also controlled by diffusion processes, occur in the near-weld zone. Avrami method [2, 3] with coefficients, determined depending on temperature and level of formation of

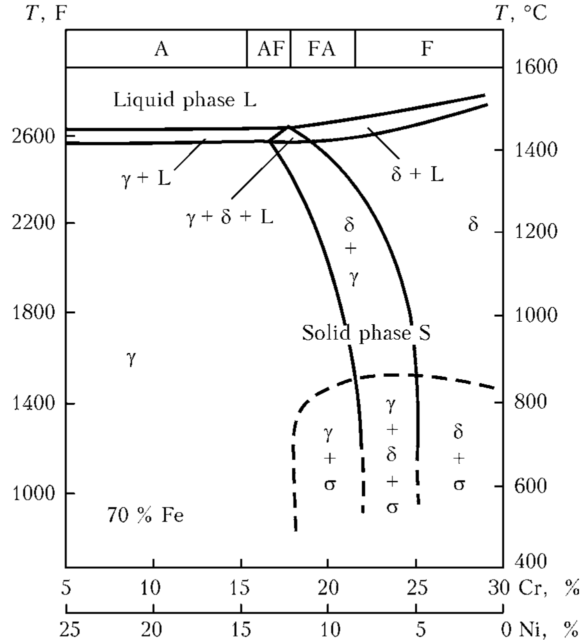


Figure 1. Phase constitutional diagram of Fe–Cr–Ni system at 70 % Fe [1]: A — austenite crystallization; AF — mainly austenite crystallization; FA — mainly ferrite crystallization; F — ferrite crystallization

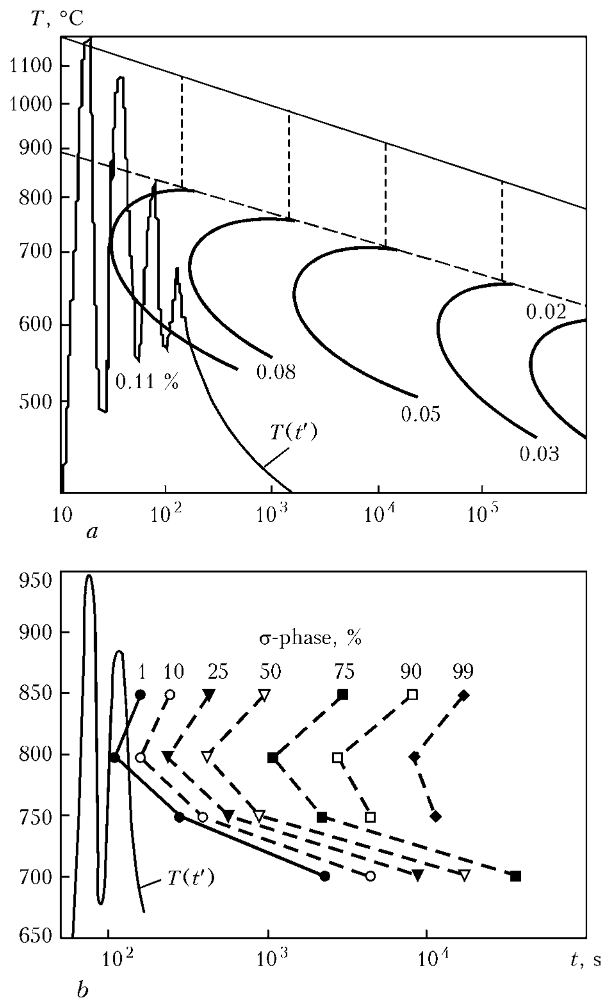


Figure 2. Temperature-time diagrams of formation of carbides in 18Cr9Ni type steel depending on content of carbon [1] (*a*) and σ-phase in DSS steel (22.4 Cr; 4.88 Ni; 3.13 Mo; 0.14 Mn; 0.67 Si; 0.18 N; 0.023 C) [2] (*b*)

new phase at given temperature in the case of very long soaking, was used in study [2] for description of the *c*-curves, related with σ-phase formation. Usage of given method is complicated by a wide spread in values of the corresponding coefficients for description of the *c*-shaped temperature-time curves of a type shown in Figure 2.

Present work proposes an approach based on a numerical integration of accumulation of effect of new phase presence in a specific point of the near-weld zone with given thermal cycle $T(t')$ based on data of corresponding *c*-shaped curve. A derivative $\partial T/\partial\tau$, proportionally to which indicated process of accumulation develops [4], can be calculated at any point of $T_{\min} < T < T_{\max}$ for it.

During formation of chemical compound (chromium carbides) (see Figure 2, *a*) the integration for an alloy with specific carbon content at $\partial T/\partial\tau \approx T/\tau$ gives

$$v_{\rm carb} = \int\limits_{\tau(T_{\max})}^{\tau(T_{\min})} \overline{v}_{\rm carb}\,\frac{dt'}{\tau(T)} \approx v_{\rm carb}\chi, \qquad (1)$$

where $\chi = \int\limits_{\tau(T_{\max})}^{\tau(T_{\min})} \frac{dt'}{\tau(T)}$ is the level of sensitization in the given point of HAZ with thermal cycle $T(t')$; $v_{\rm carb}$ is the carbide contents corresponding given *c*-shaped curve in Figure 2, *a*.

In case of the σ-phase, when intensity of the accumulation depends on temperature as well as level of already accumulated σ-phase (see Figure 2, *b*), the integration is carried out on each *c*-shaped curve, corresponding accumulated σ-phase, i.e.

$$v_\sigma = \sum_{j=1} \overline{v}_{\sigma j} \int\limits_{\tau(T_{\max})}^{\tau(T_{\min})} \frac{dt'}{\tau_j(T)}, \qquad (2)$$

where $\overline{v}_{\sigma j}$ is the cost of *j*-th *c*-curve in Figure 2, *b*.

Two specific examples will be considered. 100 % monitoring of 1451 joints of Du 300 pipeline of the primary coolant circuit of multiple forced circulation was carried out on power block No.3 of Chernobylskaya NPP in a period of mid-life repair at the end of October, 1997. 208 joints among them had defects which were qualified as cracks of intercrystalline stress corrosion. Du 300 pipelines of 325 × 16 mm section were run from April, 1981, pipe material was steel 08Kh18N10T, joints were welded by 04Kh19N11M3 grade wire providing low (not less than 0.06 %) content of carbon in the weld metal.

Intercrystalline cracks were found in the HAZ metal (Figure 3) close to inner surface. A thermal cycle, related with welding in six runs (taking into account root run), according data of [5], is shown in Figure 4. Digitized *c*-shaped curve from the Table was used. The sensitization level according to data of Figure 4

Temperature-dependent values of $\tau(T)$ for different carbon content

T, °C	C = 0.11 %	C = 0.08 %
540	754.6	–
550	635.5	–
560	546.3	1000.0
570	419.8	894.1
580	300.8	793.5
590	233.9	719.4
600	122.3	629.4
610	85.5	555.3
620	79.6	502.4
630	73.6	444.1
640	67.7	401.8
650	62.5	364.7
660	58.0	338.7
670	53.6	327.6
680	48.3	306.5
690	46.1	327.6
700	44.6	343.5
710	43.1	375.3
720	45.4	417.6
730	47.6	470.6
740	50.6	613.5
750	55.0	931.2
760	58.0	1158.8
770	64.7	–
780	71.4	–
790	85.5	–
800	94.5	–

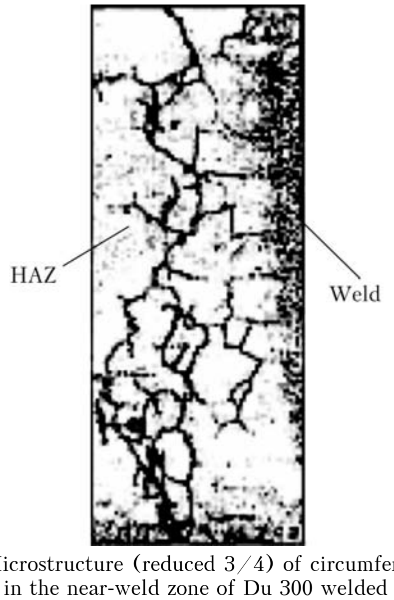


Figure 3. Microstructure (reduced 3/4) of circumferential operating cracks in the near-weld zone of Du 300 welded joint

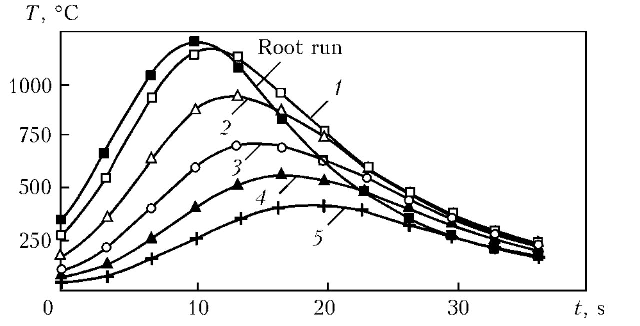


Figure 4. Temperature cycles on the inner surface at root run and next ones (1–5)

depending on run is the following: root run — 0.0085; 1st — 0.0529; 2nd — 0.0536; 3rd — 0.0306; 4–5th — 0. It is seen from these data that $\chi_\Sigma \approx 0.15$, i.e. noticeable enough level of sensitization of regions of the HAZ metal on the inner surface of pipe is present, that promoted nucleation and development of damages — cracks of intercrystalline stress corrosion, taking into account additional factors (stressed state in the HAZ metal on the inner surface of pipe and presence of corrosion medium — water of the primary coolant circuit at temperature around 280 °C). It is shown in series of works, for example [5], that the fracture toughness of the HAZ metal of 08Kh18N10T steel is at the level of 65 MPa·m$^{1/2}$ in the region of studied joints of Du 300, i.e. significantly lower of that behind the HAZ limits, where sensitization is absent.

Let us consider one more example. In 2009 in block No.2 of Rivnenskaya NPP a leak had appeared in a zone of connecting the pipeline and Du 250 T-bend (Figure 5) on Du 90 branch 273 × 20 mm of the pipeline of the primary coolant circuit. The pipeline material was steel 08Kh18N10T.

Crack-like through defect of around 150 mm length was found by means of non-destructive testing on the inner surface along the HAZ of circumferential weld with escaping on the outer surface in a form of circumferential crack (around 10 mm) of significantly smaller length. Beginning of the crack on the inner surface and ending on the outer have various axial coordinates, differing by 20–30 mm, i.e. the crack propagated not normal to pipe axis, but in a plain at an angle of 45° to this axis. If assume that found defect is the crack of intercrystalline stress corrosion, then a place of its nucleation is sensitized region of the

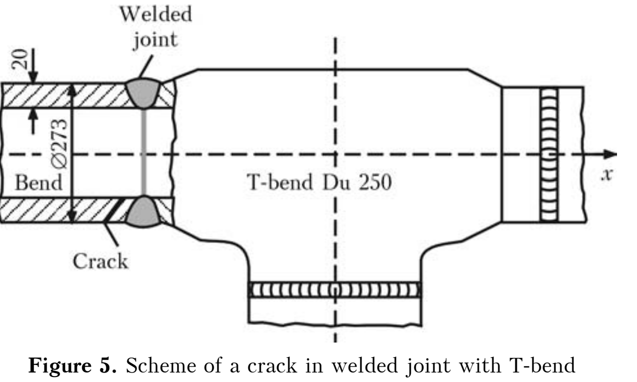


Figure 5. Scheme of a crack in welded joint with T-bend

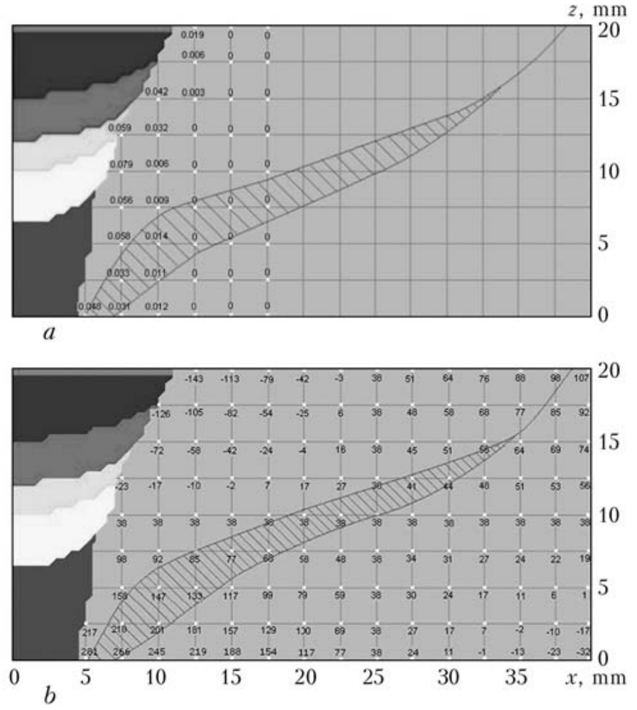


Figure 6. Possible trajectory of crack of intercrystalline stress corrosion and calculated values of χ_Σ in six run welding of butt weld (δ = 20 mm, steel 08Kh18N10T) (*a*) and transverse stresses σ_{zz} [MPa] (*b*)

HAZ on the inner surface (Figure 6, *a*) resulted from multirun (6–7 runs) effect of the thermal cycles according to types given in Figure 4. The crack propagated during a long period of time (block was implemented in 1981) under the effect of axial stresses σ_{xx} from internal pressure in the pipe:

$$\sigma_{xx}(P) = P\,\frac{R/\delta}{(2+\delta/R)}, \quad (3)$$

and residual welding stresses [6]:

$$\sigma^{w}_{xx} \approx -\sigma_0\left[\cos\frac{\pi x}{2x_1}\right]\frac{2z}{\delta}$$
$$\text{at } 0 < x < x_1,\ -\delta/2 < z < \delta/2,$$
$$\sigma^{w}_{xx} \approx -\sigma_2\left[\sin\frac{\pi(x-x_1)}{2(x_2-x_1)}\right]\frac{2z}{\delta} \quad (4)$$
$$\text{at } x_1 \le x < x_2,\ -\delta/2 < z < \delta/2,$$

where R is the inner radius of the pipe.

Approximate dependences (4), describing results of numerical calculations for circumferential welded joints of pipe on austenite steel, were built on data of [6]. Distribution parameters σ_0, σ_2, y_1, y_2 depending on $\sqrt{R\delta}$, $q_{\rm h.i}/\delta$ and $\sigma_{\rm y}$ are given in [6], i.e. for

$$R = \frac{243}{2} - 20 = 116.5\ \text{mm},\ \sqrt{R\delta} = 48.3\ \text{mm},$$
$$q_{\rm h.i} \approx 8372\ \text{J/cm}^2,\ \sigma_{\rm y} = 300\ \text{MPa}$$

gives

$$\sigma_0 = 270\ \text{MPa},\ \sigma_2 = -75\ \text{MPa},\ y_1 \approx 30\ \text{mm},\ y_2 = 75\ \text{mm}.$$

Corresponding results of calculation of sum $\sigma_{xx}(P) + \sigma^{w}_{xx} = \sigma_{xx}$ in different points (z, x) on wall of the pipe in the zone of welded joint are given in Figure 6, *b*. It can be seen from these data that a trajectory of found crack-like defect is a result of compromises between the high values of χ_Σ of material sensitization in the HAZ and tensile stresses σ_{xx} that allows considering intercrystalline stress corrosion to be a mechanism of nucleation and propagation of found defect.

Setting of a sealing coupling in the zone of indicated through defect, with which a pressure in defect zone to be similar on inner and outer pipe surfaces (between the walls of pipe and coupling), allowed rapid reduction of a risk of spontaneous defect growth. This gave the possibility to set in operation the block No.2 of Rivnenskaya NPP at the height of winter campaign of 2009 up to forthcoming middle-life repair in 2010.

CONCLUSIONS

1. It is possible enough to obtain a high level of metal sensitization, related with sensitivity to intercrystalline stress corrosion as well as metal embrittlement in the HAZ, in the near-weld zone in welding of austenite steels with a carbon content of 0.08 % and higher.

2. Application of time-temperature diagrams of formation of carbides and σ-phase for austenite steels of corresponding composition allows predicting the level of sensitization of metal according to specific thermal cycle that develops additional possibility for control of structure and properties in the HAZ metal.

1. (1998) *Welding handbook. Materials and applications*. Pt 2. Miami: AWS.
2. Elter, J.W., Palmer, T.A., Specht, E.D. (2006) Synchrotron based observations of sigma phase formation and dissolution in DSS. Ed. by H. Cerjak. In: *Mathematical modeling of weld phenomena*, 297–315.
3. Hell, E.O., Alqie, S.H. (1966) The sigma phase. *Metallurgical Rev.*, **11**, 61–68.
4. (1986) *Metallurgy and technology of welding of titanium and its alloys*. Ed. by V.N. Zamkov. Kiev: Naukova Dumka.
5. Zubchenko, A.S., Kharina, I.L., Runov, A.E. et al. (2000) Corrosion-mechanical strength of welded piping of austenitic steels of RBMK reactors. *The Paton Welding J.*, **9/10**, 45–53.
6. Makhnenko, V.I. (2006) *Safety service life of welded joints and assemblies of current structures*. Kiev: Naukova Dumka.

ON PHASE TRANSFORMATIONS IN AGGLOMERATED FLUX OF SALT-OXIDE SLAG SYSTEM AT HEATING

V.E. SOKOLSKY[1], **A.S. ROIK**[1], **A.O. DAVIDENKO**[1], **V.I. GALINICH**[2], **I.A. GONCHAROV**[2], **D.D. MISHCHENKO**[2] and **V.S. TOKAREV**[2]

[1]Taras Shevchenko National University, Kiev, Ukraine

[2]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Electron-optical and X-ray diffraction methods were used to study the structure and phase composition of agglomerated welding flux of SiO_2–Al_2O_3–CaF_2–MgO system.

Keywords: *arc welding, agglomerated welding flux, electron-optical and X-ray examination methods, interaction reactions, phase transformations*

Agglomerated flux production requires much less power consumption than fused flux manufacture. Ceramic fluxes are made by mixing charge components with binder (liquid glass) in the pelletizer with subsequent baking at the temperature of 600–700 °C [1, 2]. After long-term isothermal soaking in the molten state at 1500–1750 °C, that is higher than the flux melting temperature by 300–600 °C, fused flux is quenched by «wet granulation» (pouring a melt jet into water). Therefore, it has a structure close to that of the melt. Agglomerated flux mainly preserves the crystalline structure of the initial charge materials. The fast process of welding with agglomerated fluxes in the presence of various temperature zones in the weld pool cannot completely ensure formation of slag with preferable structures of liquid type [3], whereas description of the processes of structure formation in them is practically absent in scientific publications. Thus, integrated structural studies of agglomerated fluxes are of considerable scientific interest.

Experimental conditions. Powder-like sample of flux on graphite substrate was subjected to electron-optical examination in raster electron microscope JSM-7700F with an attachment for X-ray spectral analysis. A massive slag sample that was removed from the crucible after complete melting of the flux (1500 °C) was studied separately from the side of the bottom and the surface. To prevent the influence of charging by the electron beam in the entire low-conducting flux, a layer of pure platinum of 3 nm thickness was spray-deposited on the sample surface. X-ray analysis (CuK_α-radiation, DRON-3M diffractometer) was conducted after granulation and drying of the flux, as well as complete melting from the side of the crucible bottom and surface.

High-temperature X-ray investigations were conducted using high-temperature diffractometer, designed to study melts (MoK_α-radiation). Radiation monochromatization was performed with a couple of balanced differential Zr–Y filters [3]. Filming was conducted at temperatures of 600, 800, 1000, 1200, 1350 and 1450 °C in a high-temperature vacuum chamber in highly pure helium atmosphere.

Data of X-ray analysis were interpreted using Powdercell, Mercury structural programs, Match and Retrive data bases that are freely disseminated through the Internet. When studying the slag melt, calculations were performed using proprietary software [3].

Room temperature studies. Calculated relationship of the main components of MgO, Al_2O_3, SiO_2 and CaF_2 is given in Table 1. In the pelletizer sodium-potassium liquid glass was added to the crushed mechanical mixture of the main components. Baking at 500 °C was conducted after granulation and soaking in air. Composition of the obtained flux was determined using X-ray fluorescent analysis.

Data of X-ray phase analysis (Figure 1) show that after granulation and baking the sample contains only initial components — α-SiO_2, trigonal Al_2O_3, cubic MgO and CaF_2. X-ray phase analysis methods did not reveal any products of flux component interaction.

Table 2 gives micrographs and data of microanalysis of the sample bottom and surface after remelting in a molybdenum crucible. Micrographs of the crucible surface and bottom differ somewhat. From the bottom side the formed crystalline phases are more finely dispersed, voids are observed, in which gas bubbles accumulated, and cracks are clearly visible. The sample is not homogeneous. There is markedly less fluorine on the surface (0.99–3.50 at.%), whereas from the crucible bottom side (if we ignore the reduced amount of fluorine in the voids — reflection 1, spectrum 2), fluorine content is higher than 7 at.%. Light-coloured inclusions of the type of spectrum 3 in reflection 2 are also observed, where fluorine concentrations are considerable, although visually the area of these particles is small.

Note that the approximate ratio of components Ca:Al:Si = 1:2:2 (see Table 2) in most of the reflections corresponds to anorthite — lime felspar $Ca(Al_2Si_2O_8)$. Sodium content in these samples is

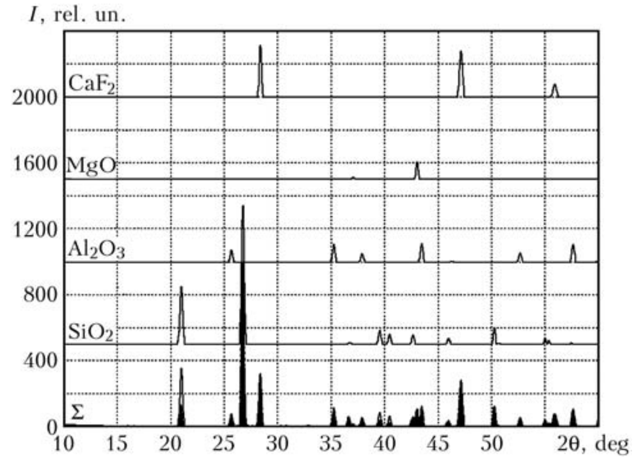


Figure 1. Roentgenograms of components of crushed to powder agglomerated flux and summation curve after improvement of profile based on SiO_2, Al_2O_3, MgO and CaF_2 elementary cells by Powdercell

much smaller than in samples before remelting. This means that alkali oxide is uniformly distributed across the volume after melting, rather than concentrating on particle surface as in the freshly prepared flux. From the bottom side fluorine content C_F is in the range of 3–16 at.%, whereas from the surface side C_F does not exceed 3.5 at.%. Fluorine content does not correlate with calcium content C_{Ca}, where $C_{Ca}/C_F \neq$ $\neq$ 1:2. Magnesium content is much higher from the bottom side than from the surface side (Figure 2). Also found here is the dependence of C_F in all the samples (both from the substrate side, and from the bottom side) on C_{Ca+Mg}, C_{Mg} and C_{Ca}. In our opinion, such a dependence of C_{Ca+Mg} with the largest of the

Table 1. Composition of flux for surfacing, wt.%

Assessment	MgO	Al_2O_3	SiO_2	CaF_2	Na_2O	K_2O	Fe_2O_3
Calcu-lated	10.0	25.0	40.0	25.0	–	–	–
Actual	8.9	22.6	42.0	22.9	1.4	0.8	1.4

three correlation coefficients, is indicative of the fact that fluorine is partially redistributed between calcium and magnesium that suggests formation of calcium oxide at the expense of magnesium oxide.

X-ray phase analysis of a sample remelted at 1500 °C (Figure 3) shows that the main phases both from the substrate side and from the crucible bottom side are the triclinic (a =0.8192 nm, b = 1.2869 nm, c = 1.4180 nm, α = 93.18°, β = 115.63°, γ = 91.08°) and monoclinic (a = 0.8235 nm, b = 0.8630 nm, c = = 0.4833 nm, α = 90°, β = 89.37°, γ = 90°) modifications of anorthite. From the bottom side MgF_2 is present is small amounts (see Figure 3). Thus, X-ray phase analysis confirms the fact that at remelting calcium and magnesium exchange anions and in anorthite calcium is present (at least partially) in the oxide form and magnesium, partially, forms fluoride.

High temperature X-ray studies in the solid state. In order to trace the sequence of the reactions in the solid phase, ceramic flux crushed into powder was placed into a molybdenum crucible, which was located on the work table of high-temperature vacuum chamber of the diffractometer for melt investigation [3], and was subjected to high-temperature X-ray phase analysis. As shown by analysis, structural changes in

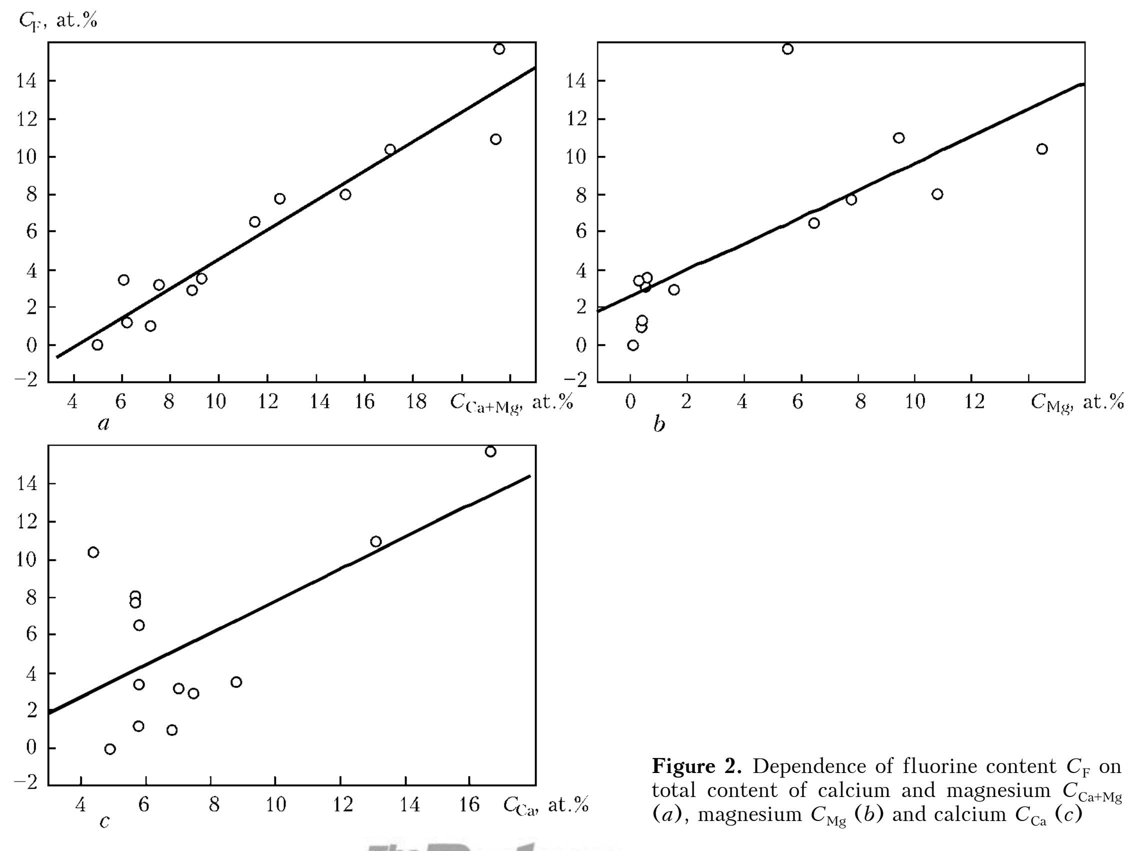
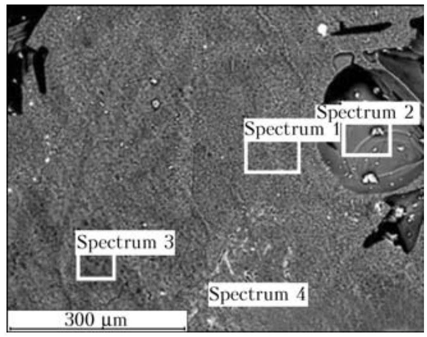


Figure 2. Dependence of fluorine content C_F on total content of calcium and magnesium C_{Ca+Mg} (a), magnesium C_{Mg} (b) and calcium C_{Ca} (c)

Table 2. Data of X-ray spectral (at.%) and visual analysis of remelted flux

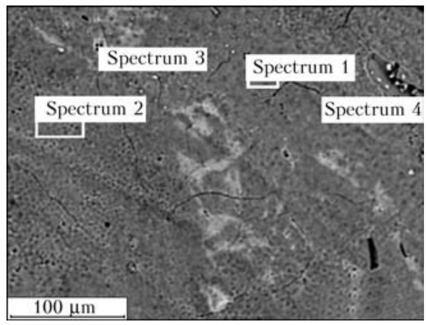
Bottom, reflection 1

Chemical element	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4
O	58.9	67.6	56.3	54.0
F	8.0	3.4	10.3	10.9
Na	0.2	0.3	0.4	0
Mg	9.5	0.3	12.7	8.3
Al	6.7	12.0	5.8	2.3
Si	11.0	11.1	10.1	11.4
Ca	5.7	5.8	4.4	13.1
Ti	–	–	<0.1	–



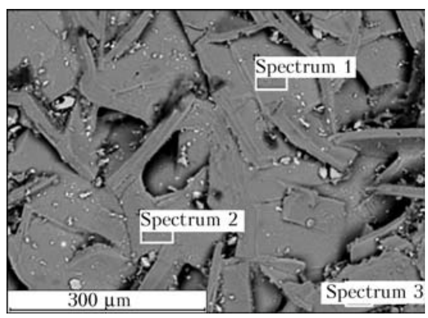
Bottom, reflection 2

Chemical element	Spectrum 1	Spectrum 2	Spectrum 3	Spectrum 4
O	59.7	60.92	51.55	63.29
F	7.7	6.48	15.63	3.17
Na	0.1	0.14	0	0.02
Mg	6.8	5.69	4.89	0.49
Al	8.8	9.48	1.22	13.25
Si	11.1	11.47	10.08	12.74
Ca	5.7	5.81	16.64	7.04



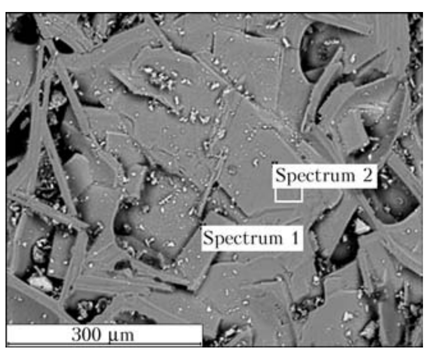
Surface, reflection 1

Chemical element	Spectrum 1	Spectrum 2	Spectrum 3
O	62.6	66.0	60.9
F	2.9	1.0	3.5
Na	0.1	0.3	0.3
Mg	1.4	0.4	0.5
Al	12.8	12.8	13.5
Si	12.7	12.6	12.6
Ca	7.5	6.8	8.8



Surface, reflection 2

Chemical element	Spectrum 1	Spectrum 2
O	72.1	67.9
F	–	1.2
Na	0.1	0.1
Mg	0.1	0.4
Al	11.7	12.5
Si	11.1	12.1
Ca	4.9	5.8



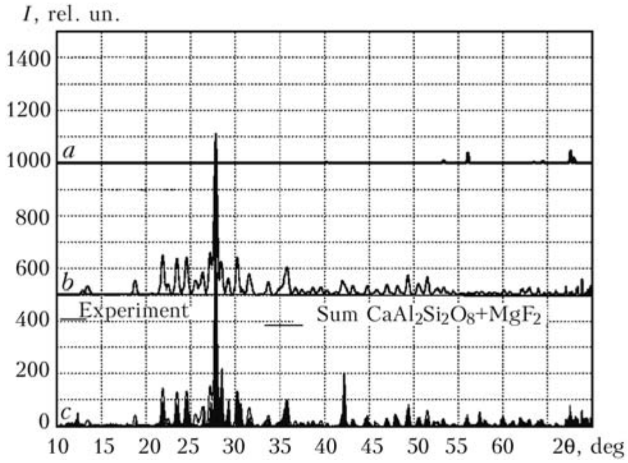


Figure 3. Diffraction patterns of flux at 1500 °C from the bottom side: *a*, *b* — improved profile of magnesium fluoride and anorthite, respectively; *c* — experiment and summary curve for monoclinal anorthite and magnesium fluoride (line with shaded area under the curve)

the sample occur in the entire temperature range (Figure 4). Up to 1200 °C these changes occur in the solid phase. At low temperatures transformations proceed slowly, and mainly run inside the phases. For instance, already at 600 °C, the most intensive peak responsible for 100 % intensity of hexagonal α-quartz decreases abruptly. At the same time, peaks appear which may be referred to other silicon modifications.

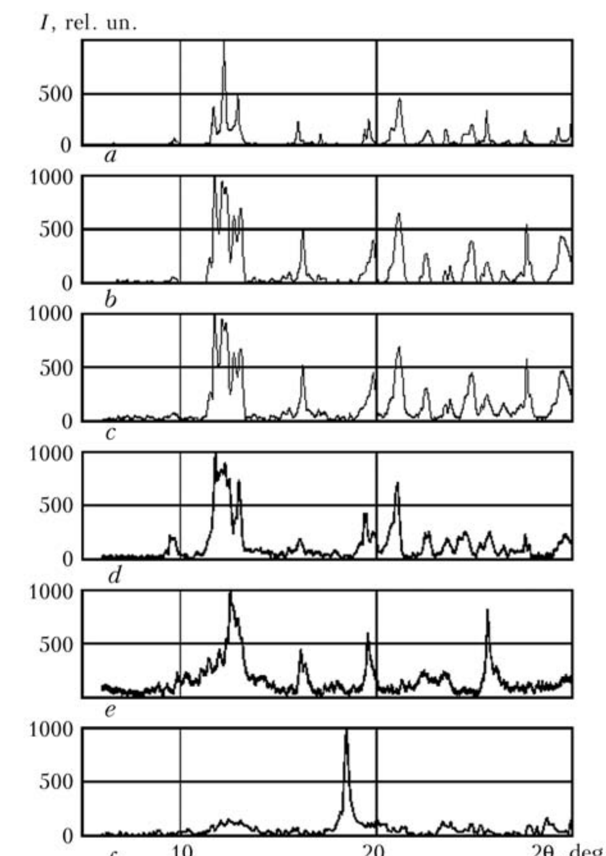


Figure 4. Diffraction patterns of flux at different temperatures: *a* — room temperature; *b*–*f* — 600, 800, 1000, 1200, 1200, 1350 °C, respectively

Interphase interactions start at higher temperatures. It should be taken into account that in an agglomerated flux the main components are inside the matrix from binder material (product of liquid glass heat treatment). Therefore, interphase interaction will occur as a result of diffusion of flux component atoms into the matrix, and vice versa. According to Sen's rule [4], diffusion rate is higher in the direction of the body with greater interatomic distances. Of all the flux components the largest interatomic distances ($R_{cation-anion}$) are realized in liquid glass manufacture from sodium-potassium silicate lump (R_{Na-O} and R_{K-O} distances), in connection with which liquid-glass based products are saturated by other flux components. Diffusion rate can be further increased as a result of vacancy formation at water evaporation from liquid glass (OH^- evaporating group and anion F^- replacing it, have close ionic radiuses of 0.118 and 0.115 nm, respectively).

Difficulties of interpretation of diffraction patterns of multicomponent materials, most of which have low symmetry, should be mentioned. For instance in Figure 5 one can see that MgF_2 reflections are overlapped by reflections of widened anorthite.

Interpretation of the obtained results should be performed using complex constitutional diagram of $Na_2O-Al_2O_3-MgO-CaO-SiO_2-CaF_2-MgF_2$, but such oxide-fluoride diagram is non-existent in scientific publications. The closest studied constitutional diagram is that of four-component $CaO-MgO-Al_2O_3-SiO_2$ system [4, 5], in which the field of anorthite solidification appears in the section of 15 % Al_2O_3 and ousts the fields of solidification of wollastonite ($CaSiO_2$) and piroxene ($MgSiO_3$). At 20 % Al_2O_3 the field of wollastonite solidification is absent, and that of piroxene is greatly narrowed. The section of 10 % MgO no longer has the field of calcium aluminate solidification, but has the fields of solidification of periclase (MgO), spinel (Al_2MgO), and cordierite ($Mg_2Al_4Si_5O_{18}$) [4]. It is characteristic that in the constitutional diagram of $CaO-MgO-Al_2O_3-SiO_2$

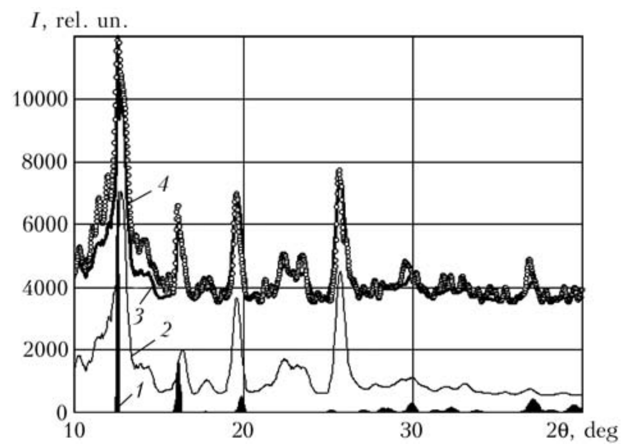


Figure 5. X-ray patterns of MgF_2 (*1*) and $Ca(Al_2Si_2O_8)$ with widened peak half-width after improvement of diffraction profile (*2*) by Powercell, total *1* + *2* (*3*) and experimental curve at 1200 °C (*4*)

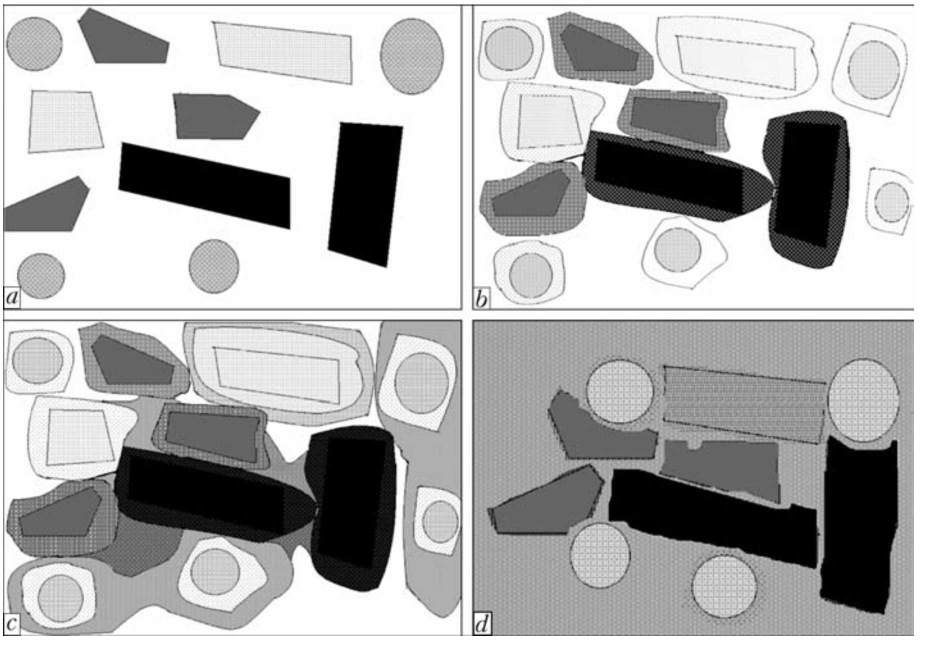


Figure 6. Structural changes at flux heating: *a–d* — first–fourth periods, respectively

system anorthite forms at small content of MgO (10–15 %), whereas spinels form at higher magnesium oxide contents.

Let us consider the mechanism of anion redistribution between calcium and magnesium cations. Let us give a simplified demonstration of chemical interaction in a mixture of solid reagents in binder material matrix (Figure 6). In the first stage components after granulation are placed into a binder matrix (Figure 6, *a*). At temperature rise diffusion on the phase contact surface increases considerably and surface layers saturated with contacting phases form in the binder matrix, based on products of liquid glass baking (Figure 6, *b*). In the third stage of the process more complex chemical compounds form that are based on interaction of boundary layers around the component inside the binding matrix (Figure 6, *c*). Further increase of temperature and component dissolution may lead to melting (probably, partial) and formation at first of local molten inclusions. Rate of substance diffusion between the molten groupings rises considerably. Diffusion between the solid and liquid components rises less significantly. Thus, at the final stage (Figure 6, *d*) a uniform liquid matrix and partially dissolved flux components form. If the silicate module of liquid glass is low, than dissolution of silicon in it with increase of silicate module may greatly lower the temperature of formation of the liquid sodium-silicate phase to 790 °C (lowest melting eutectics in Na_2O–SiO_2 has the composition of $Na_2O \cdot 2SiO_2$ + + SiO_2 + liquid, T_m = 793 °C). It is obvious that dissolution of other flux components lowers the temperature of sodium silicate. At further temperature rise, all the components either melt, or dissolve completely in the liquid phase with formation of a uniform homogeneous liquid phase.

At low baking temperatures (3rd period), more complex oxifluoride compounds, probably, form based on the products of decomposition of liquid glass and adjacent to it layer of several components (for instance, $AlCa_2Mg_5NaSi_7O_{22}F_2$). Such compounds cannot be stable in a broad temperature range, as they consist of a wide range of cations and anions with different charges and significant differences in ionic radii dimensions. Compounds of this type possibly do not have a completely formed crystalline structure or even exist in an amorphous form, as the time of their soaking at high temperatures is low (none of them were found in the roentgenograms, either). However, if they formed and then decomposed at high temperatures, then the possible decomposition of $AlCa_2Mg_5Si_7O_{22}F_2$ can be presented by one of the following equations:

$$2AlCa_2Mg_5NaSi_7O_{22}F_2 \rightarrow CaAl_2Si_2O_8 + MgF_2 + 3CaMg_3Si_4O_{12} + 2NaF, \quad (1)$$

$$2AlCa_2Mg_5NaSi_7O_{22}F_2 \rightarrow CaAl_2Si_2O_8 + 2MgF_2 + Ca_3Mg_8Si_{12}O_{35} + Na_2O, \quad (2)$$

$$2AlCa_2Mg_5NaSi_7O_{22}F_2 \rightarrow CaAl_2Si_2O_8 + MgF_2 + 3CaO + 9MgO + 12SiO_2 + 2NaF, \quad (3)$$

$$2AlCa_2Mg_5NaSi_7O_{22}F_2 \rightarrow CaAl_2Si_2O_8 + MgF_2 + 3CaO + 8MgO + 12SiO_2 + Na_2O, \quad (4)$$

proceeding from which formation of MgF_2 and anorthite should be anticipated. Such an assumption can be further confirmed by the fact that analysis of compounds of $AlCa_2Mg_5NaSi_7O_{22}F_2$ type in diffraction databases showed that all the complex oxyfluorides of this type have spatial group C 2/*m* and fluorine anions in them select magnesium cations as their closest neighbours, whereas calcium is surrounded by oxygen.

Thermal decomposition of such a compound into simpler components by one of the above formulas may lead to transformation of oxide-fluoride components

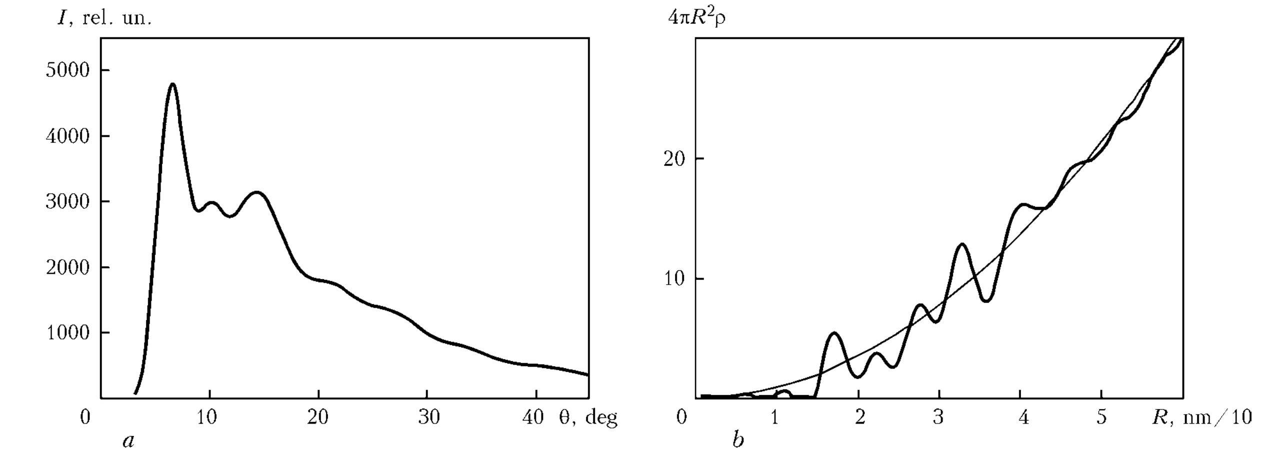


Figure 7. Curve of intensity of scattered X-rays from molten sample at 1450 °C (*a*), and curve of radial distribution of atoms (*b*)

with formation of MgF_2, CaO and anorthite. Formation of magnesium fluoride and anorthite by other mechanisms is also possible. Anorthite as fluorspar is one of the most widely spread minerals of the Earth's crust, it is identified in meteoritic material, deep material of the crust, and, possibly, in the mantle, that is indicative of its sufficient stability. Therefore, anorthite nuclei formed by one of reactions (1)–(4) can be incremented at the expense of other flux components of Al_2O_3 and SiO_2, as well as CaO_2 that formed by reaction (3), (4).

At 1200 °C the sample partially melts, and the crystalline phase also partially remains. At interaction of the liquid and solid phases there is a great increase both in the interaction surface (10^4–10^7) and intensity of mass transfer as a result of diffusion by several orders of magnitude [4]. Thus, the main components can dissolve in the liquid phase, with just crystalline anorthite (T_m = 1540 °C) and MgF_2 (T_m = 1261 °C) remaining.

At 1350 °C the diffraction pattern (see Figure 4) is unstable. In the first filming MgO reflections are present against the background of the liquid phase. One of the more complex compounds, probably, decomposed, part of which dissolved in the liquid phase. In the second and third filming MgO reflections disappear. However, crystalline peaks, which could not be identified, are present against the background of the liquid component.

X-ray examination of molten flux. Liquid phase forms completely at 1450 °C (Figure 7, *a*). It was not possible to conduct X-ray examination at higher temperatures, as the molten slag melt starts bubbling at 1500 °C, that essentially distorts the slag melt free surface, the main requirements to which are absence of microroughnesses and horizontality. As the free surface of the liquid always tries to take a horizontal position, bubbling, similar to the boiling process, greatly distorts the surface.

As shown by electron microscopy investigations, the composition of the surface and bottom of crucible does not correspond to each other. So, fluorine content is much lower from the surface side (see Table 2), than from the bottom side of the crucible, i.e. from the bottom side the oxide component is smaller and the fluoride component is larger, making the molten flux in the point of contact with the metal even more acid.

In conclusion it should be noted that the conducted investigation showed the complex nature of interaction in the agglomerated flux before formation of the molten slag phase. Main structural changes at flux heating up to 1200 °C occur as a result of solid-phase interactions in the product, formed by liquid glass sintering with the adjacent main flux components. Formation of complex compounds of $AlCa_2Mg_5NaSi_7\times$ $\times O_{22}F_2$ type is possible.

In the temperature range of about 1200 °C formation of liquid phase by melting of the agglomerate of liquid glass with the main components and of complex unstable compounds begins. Here, anion redistribution between calcium and magnesium cations takes place. This results in formation of $CaAl_2Si_2O_8$ anorthite. Another product of decomposition of complex compounds can be formation of MgF_2 as a result of fluorine being in the immediate vicinity of magnesium in them. At 1350 °C, MgF_2 is the main crystalline phase against the background of the liquid phase.

At 1450 °C complete melting of the flux is observed, the melt, however, is not homogeneous, and the structures of the bottom and surface of the formed slag crust differ markedly.

The authors express their gratitude to Tokyo Boyoki Company and personally to V.A. Tinkov, Cand. of Phys.-Math. Sci., for conducting electron microscopy investigations and providing assistance in interpretation of the obtained data.

1. Podgaetsky, V.V., Kuzmenko, V.G. (1988) *Welding fluxes*. Kiev: Naukova Dumka.
2. Podgaetsky, V.V., Lyuborets, I.I. (1978) *Welding fluxes*. Kiev: Naukova Dumka.
3. Shpak, A.P., Sokolsky, V.E., Kazimirov, V.P. et al. (2003) *Structural peculiarities of melts of oxide systems*. Kiev: Akademperiodika.
4. Pashchenko, A.A., Myasnikov, A.A., Myasnikova, E.A. et al. (1986) *Physical chemistry of silicates*. Ed. by A.A. Pashchenko. Moscow: Vysshaya Shkola.
5. Berezhnoj, A.S. (1900) *Multicomponent oxide systems*. Kiev: Naukova Dumka.

WEAR RESISTANCE AND STRENGTH OF TUNGSTEN CARBIDES $WC-W_2C$ PRODUCED BY DIFFERENT METHODS

A.I. BELY
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Investigation results are given on wear resistance and strength of particles of fused tungsten carbides $WC-W_2C$ produced by different methods: mechanical crushing of ingots, thermal centrifugal spraying and spheroidisation of powders by using the induction plasma technology.

Keywords: *hard-facing, hard-facing consumables, tungsten carbides, thermal centrifugal spraying, strength, wear resistance, hard-facing composite alloys*

Hard-facing composite alloys consisting of reinforcing particles (fused tungsten carbides) and a matrix are characterised by the maximal wear resistance under conditions of abrasive, gas-abrasive and some other types of wear. A distinctive feature of the process of wearing of such alloys is a stepwise wear of individual components of a composition. This is accompanied by the so-called shadow effect, when the more wear-resistant reinforcing particles take up the main load due to fracture forces, thus protecting the alloy matrix from wear.

Therefore, at an equal wear resistance of the matrix the performance of composite alloys is determined by their chemical composition, concentration, wear resistance and strength of the reinforcing particles. This study gives results of investigations into wear resistance and strength of the particles of fused tungsten carbides $WC-W_2C$ produced by different methods: mechanical crushing of ingots, thermal centrifugal spraying and spheroidisation of powders by using the induction plasma and other technologies [1–4].

It is a known fact that concentration of the reinforcing particles in a composite alloy is determined by their shape. The optimal shape of the particles is spherical, as it provides the maximal concentration of the wear-resistant phase, good flowability and, as a consequence, stable operation of feeding devices of the hard-facing machines [5, 6]. Figure 1 shows the data on apparent density, and Figure 2 — flowability of fused tungsten carbides with particles of the spherical and sharp-angled shapes produced by the conventional procedure [6]. These data prove advantages of the spherical shape of the particles, especially in terms of their flowability. The crushed particles of tungsten carbides do not spill at all via a funnel with a diameter of 2.5 mm.

Also, this conclusion is confirmed by measuring fill factor K_f of a strip tungsten carbide depending on the fractional composition and shape of the reinforcing particles (Figure 3). Filler metal based on the spherical tungsten carbide particles with a size of 0.28–0.45 mm has the maximal value of the fill factor, and that based on the crushed tungsten carbide particles with a size of 0.63–0.90 mm has the minimal value of the fill factor, this being attributable to their shape. The experiments were carried out by pouring of loose reinforcing particles using a strip feeder into a flute formed by the cold-rolled strip 0.3 mm thick and 18 mm wide [7].

Therefore, the spherical shape of the reinforcing particles of composite alloys is best to provide the required concentration of the wear-resistant phase in a hard-facing consumable and wear-resistant layer, as well as the stable operation of the hard-facing equipment.

Fused tungsten carbide particles of both crushed and spherical shape have approximately identical chemical composition. Hence, their wear resistance depends on strength and structure. It should be noted that owing to an increased rate of cooling of the spherical particles the thermal centrifugal spraying process

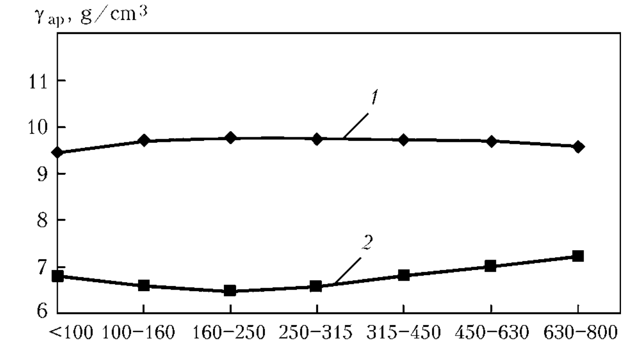


Figure 1. Apparent density γ_{ap} of spherical (*1*) and crushed (*2*) tungsten carbide particles of different size *d*

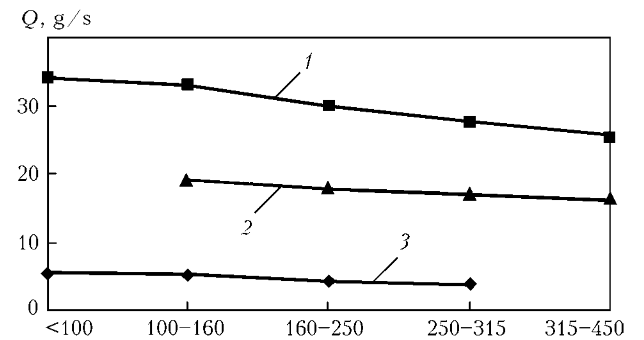


Figure 2. Flowability *Q* of spherical (*d* = 5.0 (*1*) and 2.5 mm (*3*)) and crushed (*d* = 5.0 mm (*2*)) tungsten carbide particles

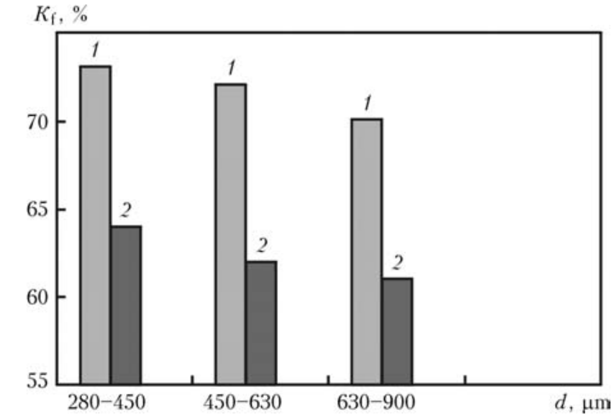


Figure 3. Dependence of fill factor K_f of strip tungsten carbide on fractional composition and shape of reinforcing particles: *1* — spherical; *2* — crushed

has a positive effect on formation of structure of the fused tungsten carbides [8].

Abrasive wear resistance of composite alloys was studied by using the NK-M machine [9, 10]. Quartz sand with a particle size of 0.05–0.50 mm served as an abrasive. The specimens were 10 mm diameter cylinders. They were made as follows. Loose reinforcing crushed or spherical tungsten carbide particles produced by different methods (SPh-1, SPh-2 and SPh-3 grades — by fuse spheroidisation of powder at world leading companies, PWI grade — thermal centrifugal

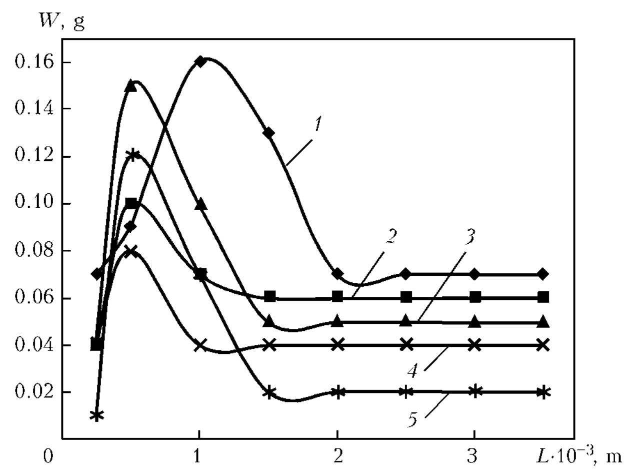


Figure 4. Dependence of wear resistance W of composite alloy with reinforcing crushed tungsten carbide particles of different particle-size compositions on friction path L: *1* — d < 180; *2* — 180–250; *3* — 250–450; *4* — 450–630; *5* — 630–900 μm

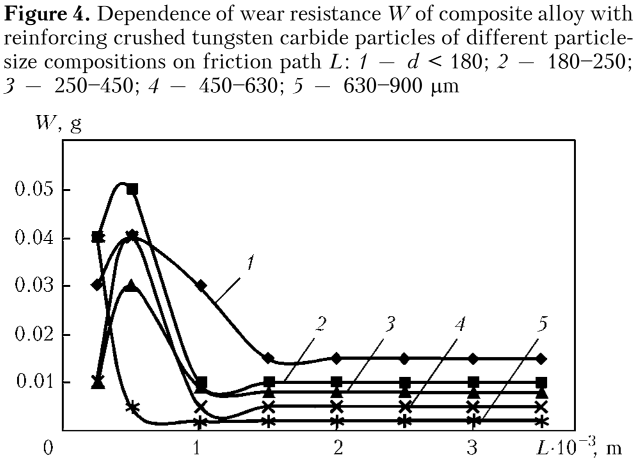


Figure 5. Dependence of wear resistance W of composite alloy with reinforcing spherical tungsten carbide particles of different particle-size compositions, produced by thermal centrifugal spraying, on friction path L: *1*–*5* — see Figure 4

spraying at the E.O. Paton Electric Welding Institute) were poured into the 10 mm diameter graphite mould. A portion of the matrix alloy of copper-nickel-manganese German silver MNMts 60-20-20 was put on top of the particles. The mould was closed by a graphite cover and intensively heated by the plasma arc. The matrix alloy impregnated the reinforcing particles. After cooling, the mould was machined along the diameter and in height. Each of five specimens had the following sizes of the tungsten carbide particles, μm: less than 180, 180–250, 250–450, 450–630 and 630–900. Wear of the specimens was estimated from loss of their weight. Specific load on a specimen was 0.5 Pa, friction rate was 0.58 m/s, and friction path L was $3.5 \cdot 10^3$ m.

The investigations conducted showed dependence of wear resistance of a composite alloy with the reinforcing crushed (Figure 4) and spherical (Figures 5 and 6) particles produced by different methods upon the friction path. The data presented indicate that wear resistance of the composite alloy with the spherical particles of the identical particle size composition is 3 or more times higher than that of the crushed tungsten carbide (see Figures 4 and 5).

Among composite alloys with the reinforcing spherical particles produced by different methods the lowest wear was exhibited by an alloy comprising the reinforcing spherical tungsten carbide particles produced by thermal centrifugal spraying (see Figure 6).

Also, it was found that run-in of the specimen wearing surfaces takes place at the initial period of the tests. For a composite alloy with the spherical particles this run-in occurs on abrasive friction path $L \approx 1 \cdot 10^3$ m, and for a composite alloy with the crushed particles — on $L \approx 2 \cdot 10^3$ m. This can be explained by an irregular shape and inconsistent strength of the crushed tungsten carbide particles, as wear, destruction and spalling of sharp angles of these particles take a longer period of run-in of the specimen surfaces.

Stabilisation of wear of specimens after run-in is a characteristic feature of the process of wear of composite alloys. Wear of specimens with the crushed tungsten carbide particles is less stable. Wear resistance of the composite alloys was found to decrease with increase in size of the particles (Figure 7). It is this fact that seems to confirm the shadow effect.

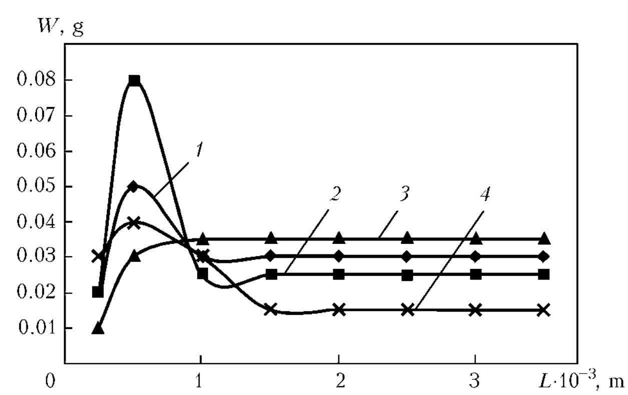


Figure 6. Dependence of wear resistance W of composite alloy with reinforcing spherical tungsten carbide particles, produced by fuse spheroidisation (*1* — SPh-1; *2* — SPh-2; *3* — SPh-3) and thermal centrifugal spraying (*4* — PWI), on friction path

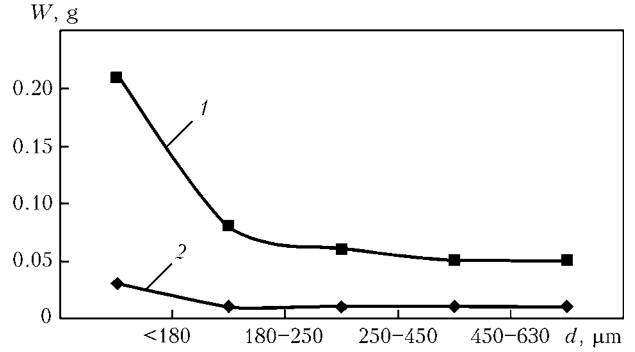


Figure 7. Dependence of wear resistance W of fused tungsten carbides on size d of reinforcing crushed (*1*) and spherical (*2*) particles at $L = 2 \cdot 10^3$ m

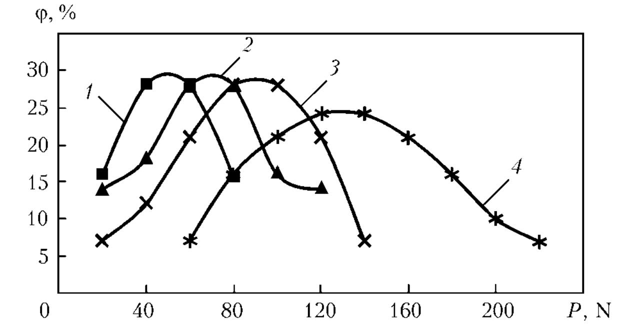


Figure 8. Strength φ of particles of crushed tungsten carbide with different particle size composition: φ — repetition frequency; P — load; *1* — d = 180–250; *2* — 250–450; *3* — 450–630; *4* — 630–900 μm

As indicated above, the process of thermal centrifugal spraying improves homogeneity of structure of the fused tungsten carbide particles, which has a positive effect on their strength. The force required to destroy them was determined by using a special device. The particles were placed between two abrasive plates and statically loaded. 40 particles of each fraction (d < 180, 180–250, 250–450, 450–630, and 630–900 μm) were subjected to the tests. It was impossible to measure strength of the less 180 μm fraction of the crushed particles because of their small size and difficulty to determine load.

Figures 8 and 9 show of the distribution of strength of the crushed and spherical tungsten carbide particles produced by thermal centrifugal spraying, having different particle size compositions. Also, strength of the spherical tungsten carbide particles with size d < < 180 μm, produced by different methods, was compared (Figure 10). As seen from the Figure, the PWI particles produced by the E.O. Paton Electric Welding Institute by the thermal centrifugal spraying method had the highest strength.

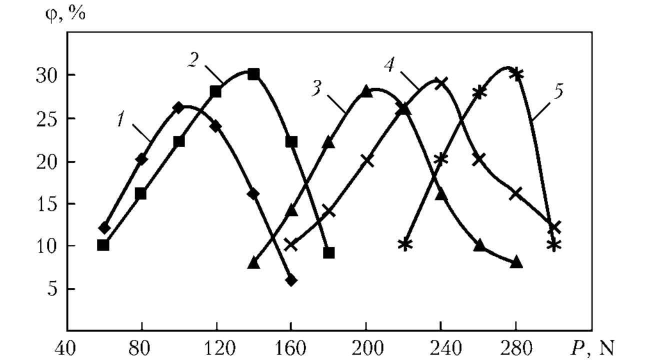


Figure 9. Strength φ of particles of spherical tungsten carbide with different particle size composition produced by thermal centrifugal spraying: *1* — d < 180; *2* — 180–250; *3* — 250–450; *4* — 450–630; *5* — 630–900 μm

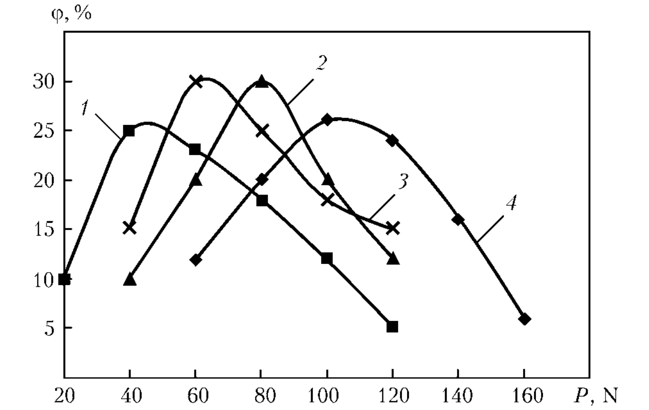


Figure 10. Strength φ of particles of spherical tungsten carbide produced by fuse spheroidisation (*1* — SPh-1; *2* — SPh-2; *3* — SPh-3) and thermal centrifugal spraying (*4* — PWI)

CONCLUSIONS

1. Spherical shape of the reinforcing particles of composite alloys is optimal for achieving a high concentration of the wear-resistant phase in hard-facing consumables and in a wear-resistant layer, as well as for providing stable operation of the hard-facing equipment.

2. As seen from the results of investigation of abrasive wear resistance of the MNMts 60-20-20 + tungsten carbide composite alloy produced by different methods, the alloy with the spherical tungsten carbide particles of the PWI grade, produced by thermal centrifugal spraying of ingots by using the E.O. Paton Electric Welding Institute technology, exhibited the lowest wear. Increase in size of the reinforcing particles increases wear resistance of the composite alloy.

3. Investigations of strength of the tungsten carbide particles produced by different methods show that the PWI particles produced by thermal centrifugal spraying have the highest strength.

1. Parenchuk, V.V., Bely, A.I., Zhudra, A.P. et al. (2001) State-of-the-art and prospects of development of production of tungsten carbide for hard-facing of drill bits. *Tsvet. Metally*, **1**, 92–93.
2. Meerson, G.A., Zelikman, A.N. (1973) *Metallurgy of rare metals*. Moscow: Metallurgiya.
3. Dignard, N.M., Boulos, M.I. (1997) Ceramic and metallic powder spheroidization using induction plasma technology. In: *Proc. of United Thermal Spray Conf*. (15–19 Sept., 1997, Indianapolis). Indianapolis: CRTP, 29–31.
4. Pawlowski, L. (1995) *The science and engineering of thermal spray coatings*. Chichester: John Wiley & Sons.
5. Gladky, P.V. (1972) *Study and development of the technology for plasma-powder surfacing*: Syn. of Thesis for Cand. of Techn. Sci. Degree. Kiev.
6. Fedorchenko, I.M., Andrievsky, R.A. (1963) *Principles of powder metallurgy*. Kiev: AN USSR.
7. Zhudra, A.P. (1980) *Study and development of materials for surfacing of composite alloys resistant to intensive abrasive wear*: Syn. of Thesis for Cand. of Techn. Sci. Degree. Kiev.
8. Yuzvenko, Yu.A., Frumin, E.I., Pashchenko, M.A. et al. (1975) Spherical tungsten carbide. Method of production and properties. *Poroshk. Metallurgiya*, **7**, 1–5.
9. Yuzvenko, Yu.A. (1978) *Study and development of consumables and technology for mechanised open arc surfacing*: Syn. of Thesis for Dr. of Techn. Sci. Degree. Kiev.
10. Yuzvenko, Yu.A., Zhudra, A.P., Frumin, E.I. (1973) Abrasive wear of composite alloys. *Avtomatich. Svarka*, **7**, 62–63.

TECHNICAL DIAGNOSTICS AND NDT

DIAGNOSTICS OF CORROSION STATE OF INNER SURFACE OF MAIN OIL PIPELINE

S.G. POLYAKOV, L.I. NYRKOVA, S.L. MELNICHUK and **N.A. GAPULA**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper gives the results of laboratory studies on development of theoretical fundamentals and procedural approach to inspection and monitoring of inner corrosion of oil pipelines and tanks. Flow chart of diagnostics of corrosion state of inner surface of oil pipeline is presented. Primary transducers were developed for inspection of oil pipeline inner surface.

Keywords: *welded oil pipeline, inner corrosion, diagnostics, corrosion rate, potential, primary transducers*

Corrosion of metals in non-electrolytes, i.e. in non-electrically conducting flow media (in oil, oil products and other organic compounds), is very dangerous for oil-transport and storage systems.

Oil is a mixture of different hydrocarbons with non-hydrocarbon components (alcohols, phenols, sulfur compounds, oxygen etc.). Pure oil products are non-electrically conducting and, therefore, electrochemical corrosion is impossible in them. However, corroding agents (water and oxygen) are always present in oil products in the amount sufficient for causing corrosion on inner surface of oil pipeline during their running. Corrosion of a bottom part of the pipeline occurs due to presence of settled water, containing dissolved salts and acids in it.

Sections on relief depressions with pipe turns (curved pieces) as well as mechanical and corrosion defects of erection welds pose particular danger for the oil pipeline due to accumulation of moisture and salts in them accelerating the processes of local corrosion dozen and hundred times. A biological factor is activated under such conditions. Changing of a nature of corrosion process is also most probably: for example, oxygen depolarization can transfer into hydrogen due to pH level change inside the defect.

Corrosion of the oil pipelines is unavoidable process as follows from mentioned above. However, knowledge of mechanism of corrosion and procedures for

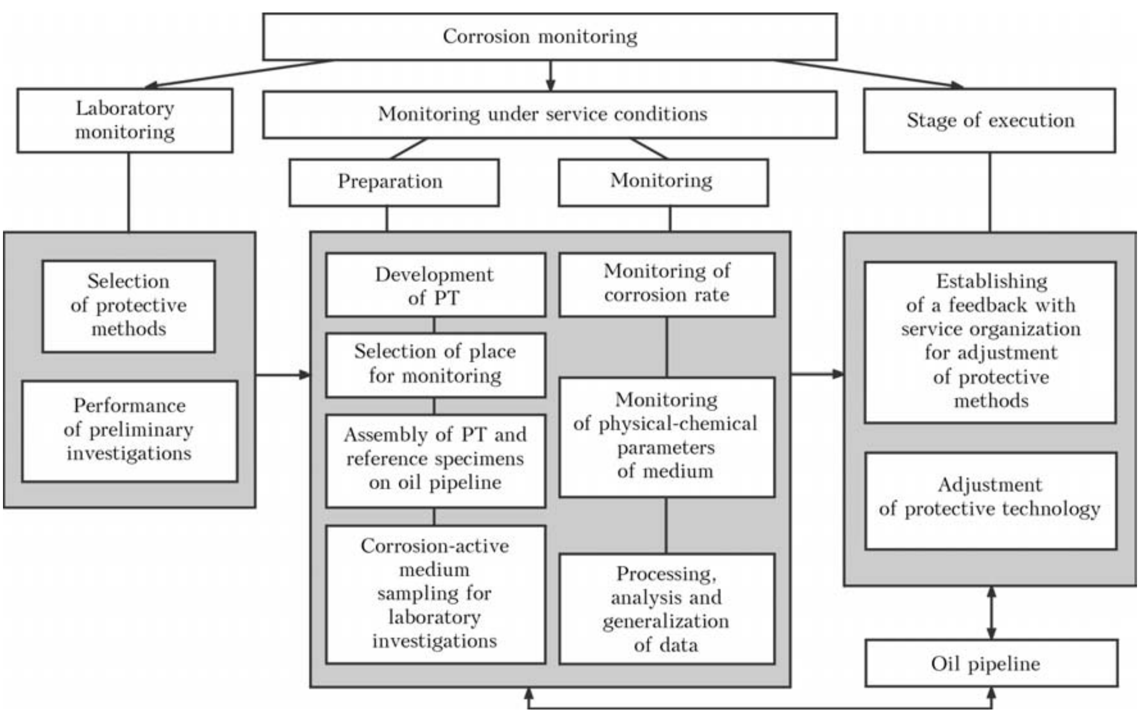


Figure 1. Flow chart of diagnostics of corrosion state of inner surface of oil pipeline

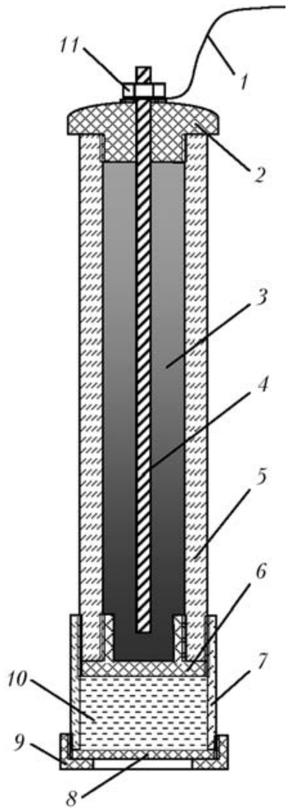


Figure 2. PT scheme for measuring potential of inner surface of oil pipelines and tanks: *1* — lead; *2* — cover; *3* — saturated solution $CuSO_4$; *4* — copper bar; *5* — casing; *6* — porous plug; *7* — additional reservoir; *8* — nanomembrane; *9* — clamping nut; *10* — saturated solution KCl; *11* — nut

its evaluation allows influencing the corrosion process, providing in this way a trouble-free operation of the pipelines for a long time. The development of an accurate procedural approach to measurement and evaluation of a rate of inner corrosion of the pipelines is necessary for their safe and reliable service [1–3]. Present paper is devoted to study of this problem.

Flow chart of diagnostics of corrosion state of inner surface of oil pipeline was developed for investigation and monitoring. In accordance with it three stages of diagnostics carrying out are proposed — laboratory monitoring, monitoring under service conditions and stage of execution. It should be noted that indicated flow chart describes a general working plan and can be adjusted depending on aim of diagnostics and available testing equipment.

Two types of primary transducers (PT) for measurement of potential (Figure 2) and corrosion rate (double- (Figure 3) and single electrode) were developed for monitoring of inner corrosion of the oil pipelines and tanks.

Laboratory investigations of medium corrosivity are an important stage of corrosion monitoring. A water-holding layer (WHL) which is applied on the surface of PT was developed for increasing accuracy of measurement of corrosion rate in oil medium. The additives, promoting absorption and retaining of moisture, were additionally introduced in the WHL. It was experimentally determined that the WHL with

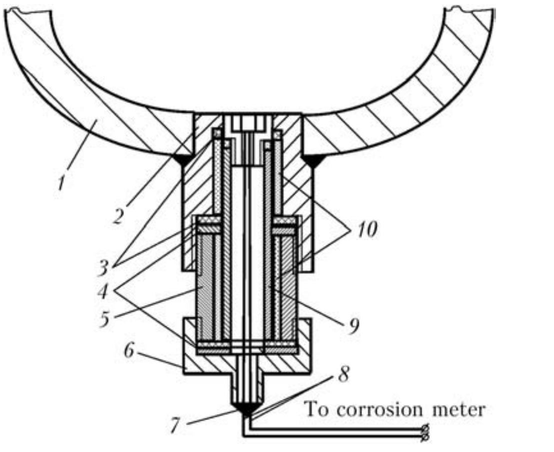


Figure 3. Scheme of double electrode PT for measuring corrosion rate mounted on the oil pipeline: *1* — pipeline; *2* — mounting fitting; *3* — seal washer; *4* — metal washer; *5* — clamping nut; *6* — cover; *7* — sealing material; *8* — leads; *9* — pipe-rod; *10* — sealing bush

10 % LiCl additive is optimum for investigations under field conditions.

Efficiency of PT with WHL was approved by means of measurement of corrosion rate for 17G1S steel in oil-water emulsion of different composition and water-free oil. Experiment results (Figure 4) showed that the developed PT with modernized WHL allows determining a value of corrosion rate at all investigated concentrations of water in oil-water emulsion. Obtained result is very important since simple PTs show, as a rule, zero values in measurements of corrosion rate in oil. 17G1S pipe steel corrosion rates were measured by two methods in the samples of oil (Nos.1–5) and water (No.6).

Equal measured volumes of oil and distilled water were mixed with the help of a magnetic stirrer at 300 rpm rate during 30 min and left to complete breakdown according to the first procedure. Water-soluble aggressive oil agents which are the reason of pipe wall corrosion transfer in a water phase and remain in it. The water phase was separated from oil with the help of funnel after breakdown of oil-water emulsion. The corrosion rate of 17G1S steel was measured on three

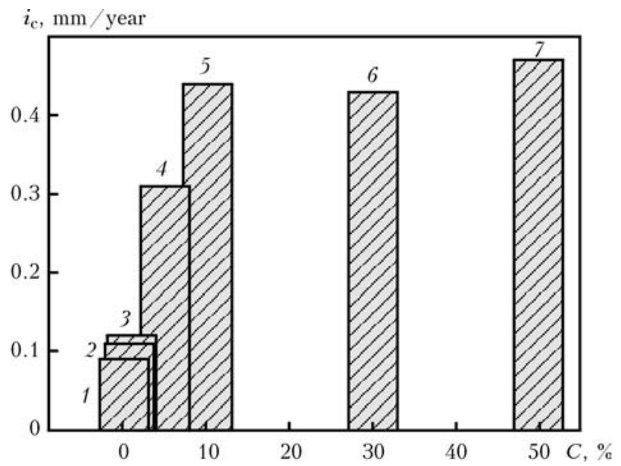


Figure 4. Changing of corrosion rate i_c of 17G1S steel depending on content *C* of 3 % NaCl in oil-water emulsion, %: *1* — 0; *2* — 0.5; *3* — 1; *4* — 5; *5* — 10; *6* — 30; *7* — 50

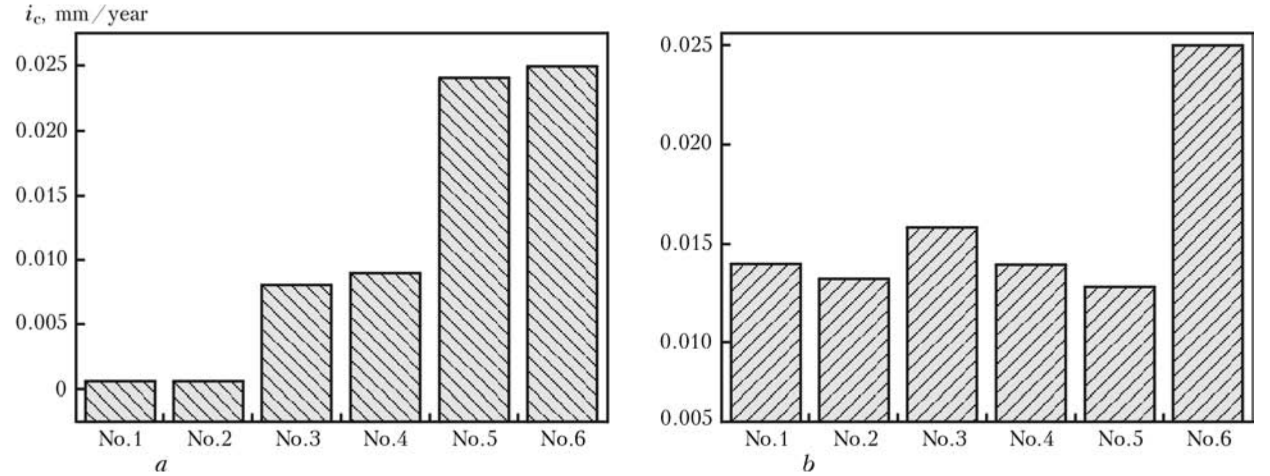


Figure 5. Results of corrosion rate measurement of 17G1S pipe steel in oil samples (Nos. 1–5) and water (No.6) obtained according to the first (*a*) and second (*b*) procedures

parallel PT in the water phase saturated with corrosion-active components. Obtained results were compared with the results of electrochemical investigations of 17G1S steel in distilled water. Emulsions made from samples 1 and 2 did not breakdown, therefore, it was impossible to determine water content in them. The measurements were carried out directly in the oil-water emulsion. Using a method of polarization resistance it was determined that the corrosion rate in these samples made 0.00063 and 0.00059 mm/year, respectively (Figure 5, *a*). It is obvious that obtained results of corrosion rate measurement were not entirely correct.

Tests on second procedure were also carried out in this connection. Before measurements PT surface was covered with WHL. The instantaneous rate of corrosion was measured in the oil samples in as-received condition (Figure 5, *b*). It follows from data obtained that application of PT with WHL allows increasing accuracy of measurement of corrosion rate in the oil medium, providing efficiency of PT for a long time and measuring corrosion rate locally in the place of moisture accumulation more accurately.

Selection of place for monitoring is one of the most important stage of preparation to monitoring under service conditions. Scanning of inner surface of oil pipeline with the help of PT for potential measurement (see Figure 2) can be carried out for selection of the place where the monitoring of inner surface of oil pipeline is planned to be done. In our opinion, it is reasonable to consider a method of introduction of PT for potential measurement on the pipe inspection gear (PIG). Modular structure of inspection PIGs of Rosen type allows joining several technologies for in-tube monitoring in one PIG. In this connection, the module for potential measurements can be used in combination with such technologies as record of data about the oil pipeline (about temperature, pressure and other physical parameters), determination of intrinsic geometry of oil pipeline, identification of transversally and longitudinally oriented defects, detection of cracks and other defects of welds.

We propose you to examine a procedure of investigation of inner surface of oil pipeline on a laboratory bench which is to be a pipe section with a weld having artificial defects. Defects geometry is so that water and corrosion products can be accumulated in them.

Clamping cell with cover was screwed to the pipe section. In order to carry out the measurements inside the weld, the cover is freely moved along the cell and fastening hole of the PT for measuring potential or corrosion rate. Weld defects were filled with water and damped flux which was used as a water and salt-holding layer. The cell was oil-filled. The results of potential measurements are shown in Figure 6. It was determined that the potential was equal zero in the points of oil pipeline surface free from moisture and its value varied from –0.5 to –0.6 V in the artificial defects.

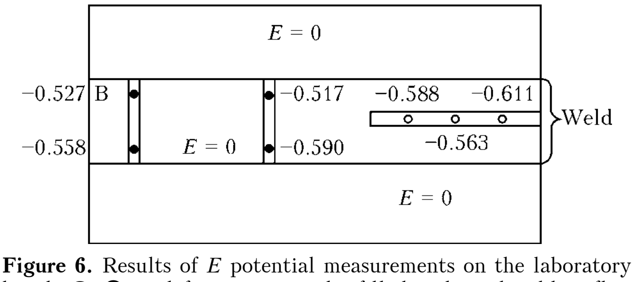


Figure 6. Results of *E* potential measurements on the laboratory bench: ○, ● — defect, respectively, filled with used welding flux saturated with 3 % NaCl solution and distilled water

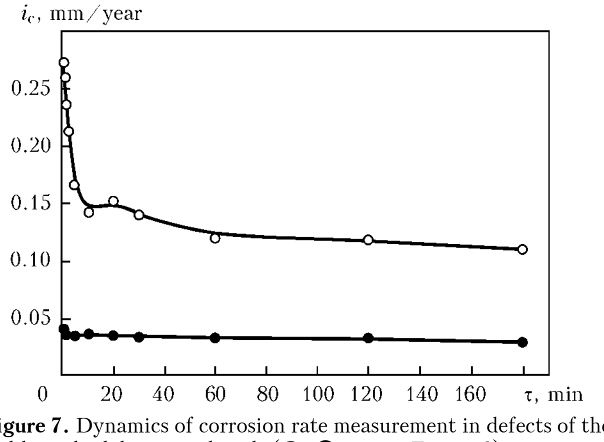


Figure 7. Dynamics of corrosion rate measurement in defects of the weld on the laboratory bench (○, ● — see Figure 6)

Measurement results of corrosion rate, mm/year, on test coils Nos. 1–3 of OTS «Luganskaya» obtained by different methods

Place of analysis in a coil	Massmetry method	Polarization resistance method
No.1		
Top	0.00081	0.010
Middle	0	
Bottom	0.00080	
No.2		
Top	0.00081	0.011
Middle	0	
Bottom	0.00240	
No.3		
Top	0.00321	0.020
Middle	0.00078	
Bottom	0.00240	

Corrosion products accumulate in the places, where the values of pipe wall potential obtained with the help of PT for potential measurements differ from zero, and dangerous corrosion situation appear. At that, more detailed control of inner corrosion in dynamics is necessary. Setting of PT for corrosion rate measurements (single and double electrode) is reasonable in such places. Type of PT for corrosion rate measurements and arrangement of its mounting depend on peculiarities and geometries of dangerous area. The rate of corrosion in time was determined for different defects on the laboratory bench, where presence of moisture was found with the help of PT for potential measurements. As a result of investigations carried out it was determined that corrosion took place in the defects with moisture accumulation, and sample surface did not fall under corrosion failure (Figure 7) in the places situated in the immediate proximity to them. Local corrosion was most intensive under the flux layer in defects of weld that was evidenced by more negative potential values and higher corrosion rates.

Test coils of OJSC «Ukrtransnafta» were used for approval of developed procedure and PT for corrosion rate measurements on inner wall of oil pipeline. Three coils were installed on OTS «Luganskaya». Coil 1 was filled with pure oil, 2 — oil with inhibitor (2 % solution of inhibitor TAL-25-13R in oil), coil 3 was empty (simulation of pipe cleaned from oil).

Reference specimens for massmetric measurements were situated in the test coils. PTs were mounted in the bottom part of coils so that their working surface became a part of inner surface of oil pipeline (Figure 8). Such PT positioning in particular is necessary for objective representation of corrosion state of inner wall of oil pipeline. It is seen from the results of corrosion rate measurements, given in the Table, that corrosion rate in the bottom part of test coils made, mm/year: coil 1 — 0.0008; 2, 3 — 0.0024. Using the method of polarization resistance the following values of corrosion rate were obtained, mm/year: coil 1 — 0.01; 2 — 0.011; 3 — 0.02.

It can be concluded that data obtained with the help of the method of polarization resistance are most reliable based on investigation results. In series the reference specimens, which were situated in the bottom part of test coil, had normal positioning to the bottom surface of oil pipeline. At that water did not accumulate on the specimen surface, flowed down from it and accumulated on the coil bottom.

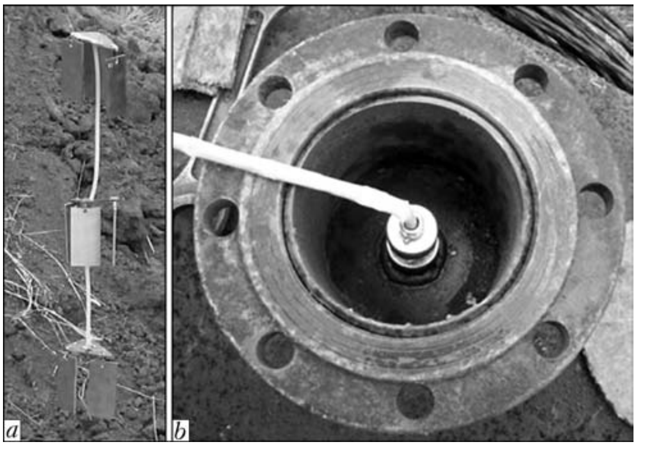


Figure 8. Series of reference specimens (*a*) and appearance of PT for measurement of rate of oil pipeline inner corrosion (*b*)

It was provided for by PT location that its working surface is the part of inner surface of oil pipeline where moisture was accumulated. Therefore, corrosion pattern on the PT surface is more close to real one. This explains spread in data about corrosion rate, obtained by methods of polarization resistance and massmetry. Besides, the corrosion rate has the highest values at the first moment of contact of metal surface with the corrosion medium and it significantly slows down in time. The approval of PT for measurement of rate of inner corrosion, carried out on three test coils of OJSC «Ukrtransnafta», confirmed their working capacity.

Thus, the structural scheme of diagnostics of corrosion state of inner surface of main oil pipelines was developed. Organization and maintenance of a feedback between the oil pipeline and service organization is an important condition for monitoring that allows effectively adjusting technology and method of oil pipeline protection. The values of corrosion rate at any concentrations of water in oil-water emulsion as well as water-free oil can be determined using PT with modernized WHL. It was determined that the local corrosion has most intensive development under the flux layer in the defects of weld. Working capacity of developed PT for determination of corrosion rate of inner wall of oil pipeline was shown by the approval, carried out on test coils of OJSC «Ukrtransnafta».

1. Chviruk, V.P., Polyakov, S.G., Gerasimenko, Yu.S. (2007) *Electrochemical monitoring of technogeneous media*. Kyiv: Akademperiodika.
2. Polyakov, S., Nyrkova, L., Melnichuk, S. et al. (2008) Procedural approach to study of inner corrosion of main oil pipelines. *Fiz.-Khimich. Mekhanika Materialov*, **7**, 756–760.
3. Polyakov, S., Nirkova, L., Melnichuk, S. et al. (2010) Evaluation of corrosion-electrochemical state of inner surface of main oil pipeline using nanomembranes. *Ibid.*, **8**, 631–634.
4. Polyakov, S.G., Gapula, N.O., Melnichuk, S.L. et al. *Primary corrosion-measuring transducer*. Pat. Ukraine on utility model 41966. Int. Cl. G01N17/00. Publ. 25.06.2009.

ENERGY CHARACTERISTICS OF THE PROCESSES OF FLASH-BUTT WELDING AT ALTERNATING AND DIRECT CURRENTS

S.I. KUCHUK-YATSENKO, P.M. RUDENKO, V.S. GAVRISH, V.P. KRIVONOS, V.M. SIDORENKO, Yu.S. NEJLO and **K.V. GUSHCHIN**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Main energy parameters of flash-butt welding machines are considered. It is shown that a.c. machines have higher values of main parameters.

Keywords: *flash-butt welding, alternating and direct current machines, energy parameters*

Selection of equipment for flash-butt welding is one of the main issues in development of the technology of welding various structures. There exist a large number of flash-butt welding machine types, using different principles of electric energy conversion [1, 2]. Therefore, it is rational to compare the currently available power sources for flash-butt welding machines. Some of these issues are considered in study [3].

At present single-phase (two-phase) power sources for power supply from 50 (60) Hz a.c. mains and three-phase sources with the following circuits have become the most widely accepted for powering flash-butt welding machines:

- from frequency converters and number of phases;
- from rectified voltage of commercial frequency;
- from higher frequency rectified voltage generated by an inverter;
- from an inverter of 40–60 Hz frequency.

Effectiveness of application of these sources (mainly by energy parameters) is assessed using the following parameters: efficiency η, power factor $k_{\rm m}$, coefficient of utilization of machine power χ.

Efficiency η is equal to a ratio of active power $P_{\rm c}$, released in the welding contact, to active power at welding machine input $P_{\rm in}$. For a.c. machine

$$\eta = P_{\rm c}/P_{\rm in} = R_{\rm c}/(R_{\rm c} + R_{\rm sh.c}), \quad (1)$$

and for a machine with rectification in the secondary circuit

$$\eta = P_{\rm c}/P_{\rm in} = R_{\rm c}/[(R_{\rm c} + R_{\rm sh.c}) + \Delta U(I_{\rm w})/I_{\rm w}], \quad (2)$$

where $R_{\rm c}$, $R_{\rm sh.c}$ are the resistance of parts being welded and ohmic resistance of machine short-circuiting; $\Delta U(I_{\rm w})$ is the voltage drop on the rectifier; $I_{\rm w}$ is the welding current.

Welding machine power factor

$$k_{\rm m} = P_{\rm in}/(UI) = (R_{\rm c} + R_{\rm sh.c})/Z, \quad (3)$$

where U, I is the effective value of voltage and current at welding machine input; Z is the impedance of the machine and parts being welded.

When at the input of electric energy receiver (welding machine) voltage is sinusoidal, and current is not sinusoidal (at phase regulation), active power consumed by the machine is determined only by the fundamental harmonic

$$P_{\rm in} = U_1 I_1 \cos \varphi_1,$$

where U_1, I_1 are the mean-root-square voltage and current at welding machine input, and $\cos \varphi_1$ for the first harmonics.

It is obvious that $U_1 = U$, as voltage at machine input is sinusoidal and

$$k_{\rm m} = U_1 I_1 \cos \varphi_1/(UI) = \nu \cos \varphi_1, \quad (4)$$

where $\nu = I_1/I$ is the coefficient of distortion, as current at welding machine input, may be nonsinusoidal.

Coefficient of utilization of machine power is

$$\chi = P_{\rm c}/(UI) = P_{\rm c}/(P_{\rm in}/k_{\rm m}) = \eta k_{\rm m}. \quad (5)$$

From expressions (1)–(5) it is obvious that

- η is independent on the angle of valve switching on and is determined by the ratio of resistances of secondary circuit and parts being welded;
- with increase of the angle of valve switching on that leads to increase of current curve distortion, power factor drops compared to full phase switching on and coefficient of machine power utilization drops, accordingly;
- η, $k_{\rm m}$ and χ values of the flash-butt welding machine can be improved by lowering the machine short-circuiting resistance $R_{\rm sh.c}$, $X_{\rm sh.c}$, $Z_{\rm sh.c}$ at optimization of machine circuit dimensions and shape, as well as lowering of power source frequency.

In resistance and flash-butt welding a.c. and d.c. (rectified) power sources are mainly used [4–7].

PWI developed and manufactured d.c. machine for flash-butt welding based on K-724 machine to determine the main energy characteristics of processes in a.c. and d.c. welding. Used as the power source was three-phase rectifier of «RoMan» Company containing three single-phase transformers, the primary windings of which are connected in a triangle circuit. A full-wave two-arm rectifier is assembled on the base of each transformer. Three diodes are connected in parallel in each arm. Thus, the rectifier has 18 diodes (Figure 1).

Rectifier specification

Rated power, kV·A	180 at 50 % duty cycle
Primary voltage/frequency, V/Hz	400/50
Secondary alternating voltage, V	5.55
Constant output voltage, V	7.4
(at rectifier powering from 380 V mains constant output voltage is 7.1 V)	

The rectifier is designed as one module. Transformers and diodes mounted on heatsinks have water cooling.

Thyristor contactors controlled by the local computer system KSU KS [7] and industrial computer of upper level system CS for control of the welding machine as a whole are connected in series with transformer primaty windings (Figure 2). Sensors of the main electrical parameters: voltage at rectifier output U_r and machine grips U_{gr}, welding current I_w and currents in phases I_A, I_B, I_C are connected to input of ADC built into control system CS. Signal converters with galvanic insulation PSA-01.01.14.18.03 of PROMSAT, Ltd. (Kiev) were used for voltage measurement. These converters have measurement range from 0 up to 10 V at input signal frequency from 0 up to 1 kHz. Current transformers were used as phase current sensors. A rectification circuit was assembled for welding current measurement, with phase current transformer outputs being connected to its input.

Rectifier output voltage is determined by mean value during the repeatability period $T_{rep} = \pi/3$,

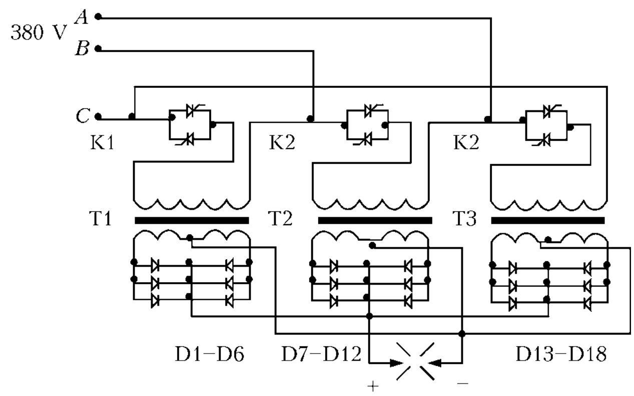


Figure 1. Electric diagram of d.c. flash-butt welding machine

which is equal to the time interval of simultaneous operation of a pair of valves in each arm:

$$U_{d0} = ((3\sqrt{3})/\pi)U_{2l} = 2.34U_{2ph},$$

where U_{2l}, U_{2ph} are the linear and phase voltage, respectively.

Regulation of secondary rectified voltage is performed by changing the angle of connection of thyristor contactors α.

Phase regulation leads to increased ripple of secondary voltage. Coefficient of rectified voltage ripple is determined as the ratio of first harmonic amplitude to mean voltage value:

$$K_{rip} = U_{m1}/U_d = (2/m^2 - 1)\sqrt{1 + m^2 \,\mathrm{tg}^2\, \alpha},$$

where $m = 6$ is the number of pulsations for a three-phase full-wave rectifier.

For $\alpha = 0°$ $K_{rip} = 0.057$, and for $\alpha = 30°$ $K_{rip} = 0.2$.

Design features of mechanical part of K-724 machine and rectification module with power transformers, powerful diodes and thryistors did not permit placing this module in immediate vicinity of welding machine grips. As a result, ohmic resistance and in-

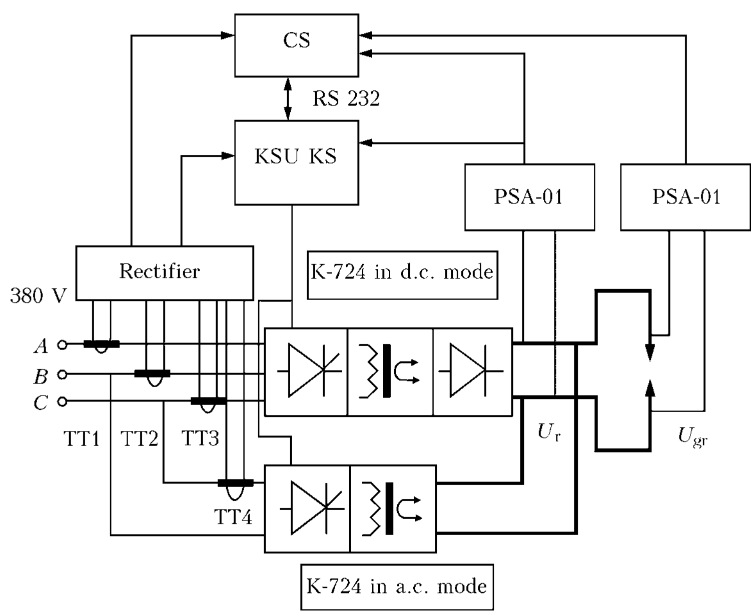


Figure 2. Block-diagram of connection of recording devices and control system of K-724 machine

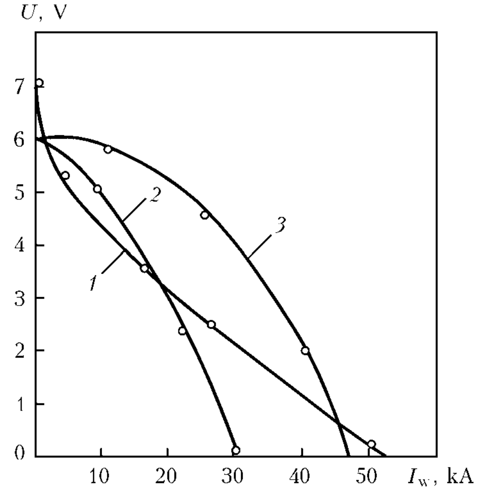


Figure 3. External characteristics of K-724 machine at powering by direct (*1*) and alternating current with standard (*2*) and optimized (*3*) circuit

ductive reactance of the welding circuit turned out to be higher than in some a.c. machines. A.c. power to the machine was supplied by welding transformer of TK-2008-6 type, the design of which allowed connecting it both to the point of rectifier connection (practically standard circuit), and to the point located in immediate vicinity of machine grips (optimized circuit). Parameter calculation was performed for these two variants.

Measurement and calculation results were used to plot external characteristics of the welding machine (Figure 3), as well as dependencies of useful power (active power released in the welding circuit) on load current (Figure 4) for alternating and direct current. The following values were assumed when plotting these dependencies: range of welding current variation I_w = 5–40 kA, voltage drop on diodes of rectifier

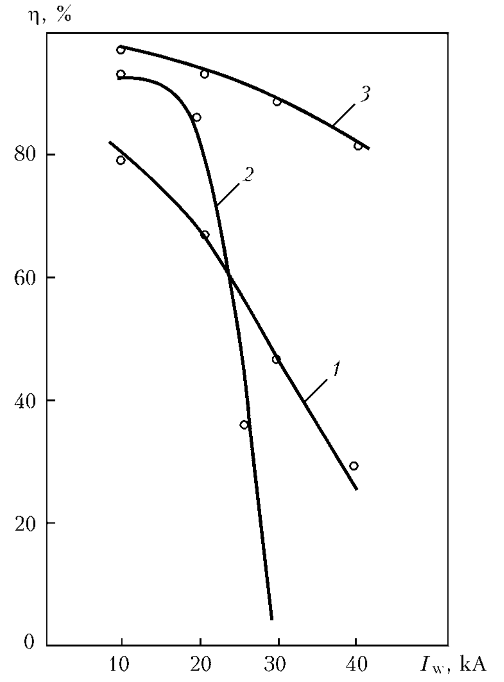


Figure 5. Dependence of efficiency of K-724 machine on welding current value at powering by direct (*1*) and alternating current with standard (*2*) and optimized (*3*) circuit

module of «RoMan» Company (three diodes connected in parallel) ΔU = 0.57 V at I_w = 10 kA, ΔU= = 1.1 V at I_w = 40 kA, circuit ohmic resistance R = = 32 μOhm, circuit inductance L = 0.7 μH, resistance $R_{sh.c}$ = 96 μOhm.

Parameters of welding transformer of TK-2008-6 type for a.c. machine are as follows: U_2 = 6 V, ohmic resistance of transformer windings R_t = 13.6 μOhm, reactive inductance X_t = 16 μOhm. To create equal

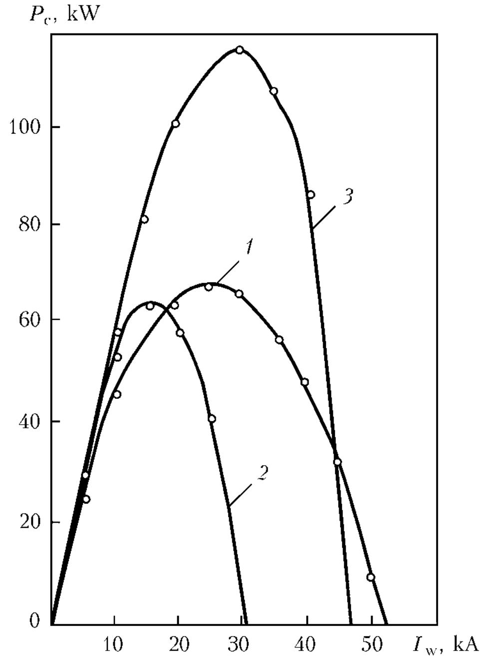


Figure 4. Dependencies of useful power of K-724 machine on load current at powering by direct (*1*) and alternating current with standard (*2*) and optimized (*3*) circuit

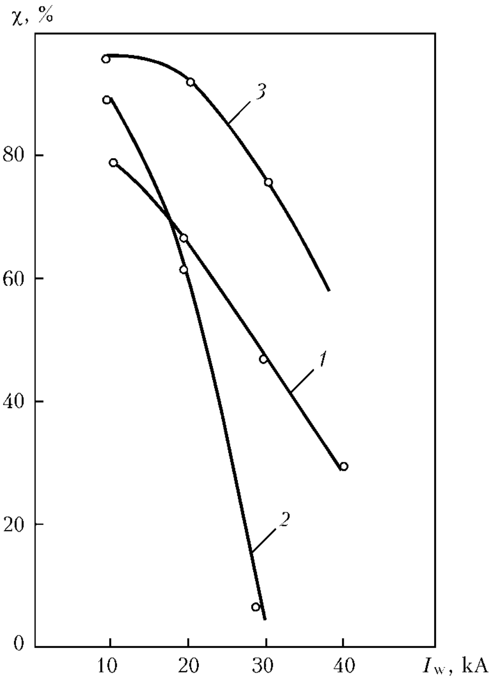


Figure 6. Dependence of coefficient of utilization of K-724 machine power on its welding current at powering by direct (*1*) and alternating current with standard (*2*) and optimized (*3*) circuit

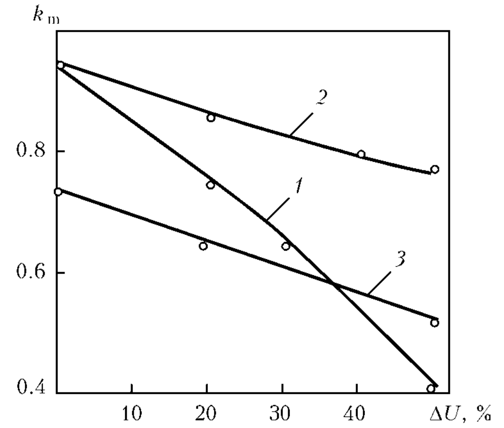


Figure 7. Dependence of power factor of K-724 machine on relative change of voltage at its phase regulation at powering by direct (*1*) and alternating current with standard circuit at welding current of 10 (*2*) and 20 (*3*) kA

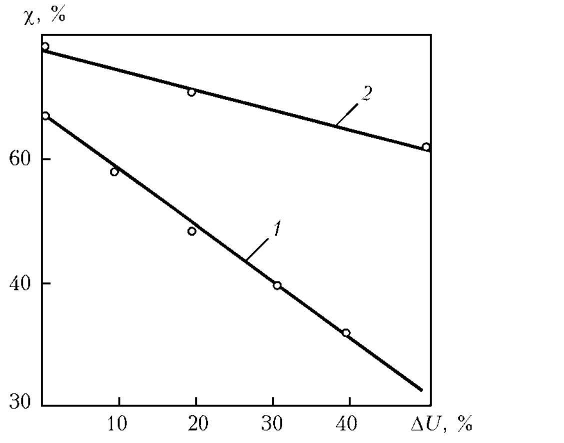


Figure 8. Dependence of the coefficient of utilization of power of K-724 machine at powering by direct (*1*) and alternating current with standard circuit (*2*) and welding current of 10 kA at phase regulation

conditions for source operation, voltage U_2 was decreased by the value of voltage drop on the diodes.

It is seen from dependencies $P_c = f(I_w)$ (see Figure 4) that useful power in a.c. welding essentially depends on circuit dimensions. In the main welding current range (10–20 kA) useful power of a.c. machine is higher than that of d.c. machine even with a standard circuit.

Dependencies of efficiencies of d.c. and a.c. machines plotted by formulas (1), (2), are given in Figure 5. Dependencies of the coefficient of utilization of d.c. and a.c. machine power plotted by formula (5) are given in Figure 6. Here also these parameters are higher for a.c. machine in the main range of welding current.

As voltage regulation in welding machines is performed mainly by phase method, it is necessary to assess the influence of the angle of switching on the thyristors on energy parameters. With this purpose, computer simulation using MatLab program was conducted and dependencies $k_m = f(\Delta U)$, $\chi = f(\Delta U)$ with phase regulation were plotted (Figures 7 and 8). The range of regulation by welding transformer current and voltage of 1:2 was considered as the most widely accepted one. It is seen that a.c. machine has higher parameters.

An important characteristic of powerful welding machines is their electromagnetic compatibility, i.e. the ability to function without deterioration of parameters of general mains. In operation flash-butt welding machines have an essential influence on all the quality characteristics of electric power. These are, primarily, fluctuations and drops of mains voltage, asymmetrical load of three-phase mains, harmonic components of current and voltage. Welding machines essentially are a source of electromagnetic interference that has an adverse influence both on welding machines proper, and on other current receivers powered from the same mains. Current sources for welding machines should be selected with a minimum level of electromagnetic interference, the admissible level of which is determined by standards of power quality in general purpose power supply mains [8].

As almost all flash-butt welding machines are fitted with thyristor contactors, then depending on the angle of switching on welding current can have different spectra of harmonic components of current. Thus, these machines are sources of higher current harmonics. Value of current components by different harmonic determines the electromagnetic compatibility of welding machines and is specified in standards.

Dependence of total harmonic distortion K_{THD} on relative voltage at phase regulation is given in Figure 9. At the same change of voltage d.c. machines have smaller total harmonic distortion. In this connection, it is rational to regulate the voltage of a.c. machine using an autotransformer or welding transformer stages.

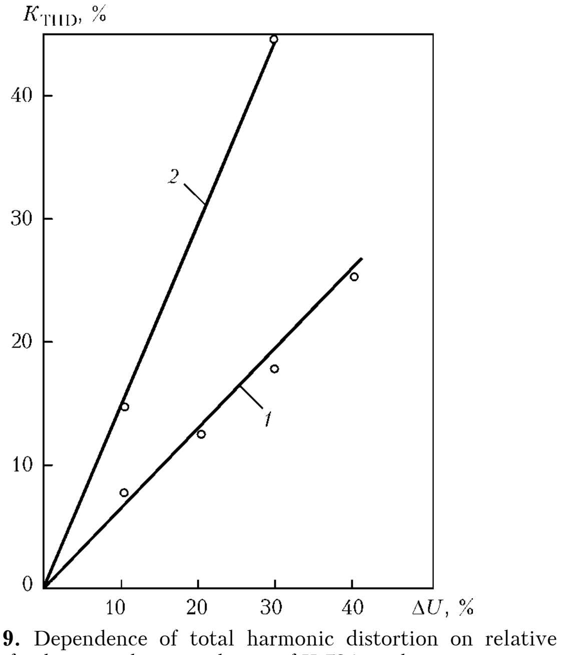


Figure 9. Dependence of total harmonic distortion on relative change of voltage at phase regulation of K-724 machine at powering by direct (*1*) and alternating current with standard circuit (*2*)

CONCLUSIONS

1. Such energy parameters as efficiency, power factor, coefficient of utilization of power in the working range of current and voltage for butt welding are higher in a.c. machines than in d.c. machine.

2. Main advantage of three-phase power sources compared to single-phase machines is related to better characteristics of electromagnetic compatibility, here uniform load is applied to mains phases and phase current decreases by 18 % at the same consumed power.

3. Lowering of the reactive component of secondary circuit resistance practically to zero when a rectifier is used in the secondary circuit does not lead to lowering of secondary circuit impedance, because of the features of machine design. Application of diodes introduces additional electrical resistance into the circuit.

4. Cost of power components of single-phase source is at lest 12 times lower compared to the considered rectifier source.

1. Paton, B.E., Lebedev, V.K. (1969) *Electric equipment for resistance welding*. Moscow: Mashinostroenie.
2. (1986) *Technology and equipment for resistance welding*. Ed. by B.D. Orlov. Moscow: Mashinostroenie.
3. Kuchuk-Yatsenko, S.I., Nejlo, Yu.S., Gavrish, V.S. et al. (2010) Prospects of increasing energy characteristics of flash butt welding (Review). *The Paton Welding J.*, **2**, 23–27.
4. Lebedev, V.K. (1992) Effectiveness of application of d.c. machine for resistance welding. *Avtomatich. Svarka*, **11/12**, 3–6.
5. Lebedev, V.K., Pismenny, A.A. (1998) Improvement of power systems of resistance welding machines. In: *Welding and related technologies — to 21st century*. Kiev: Naukova Dumka.
6. Lebedev, V.K., Pismenny, A.A. (2001) Power systems of resistance welding machines. *The Paton Welding J.*, **11**, 28–32.
7. Rudenko, P.M., Gavrish, V.S. (2007) KSU KS 02 system for automatic control and monitoring of resistance spot welding process. *Ibid.*, **11**, 34–36.
8. Zharky, A.F., Palachev, S.A. (2005) Legislative control of emission of current high harmonics in power supply systems of EU countries. *Tekhnich. Elektrodinamika*, **6**, 57–61.

RESEARCH AND DEVELOPMENTS OF THE E.O. PATON ELECTRIC WELDING INSTITUTE IN THE FIELD OF ELECTRIC ARC WELDING AND SURFACING USING FLUX-CORED WIRE (Review)

I.K. POKHODNYA, V.N. SHLEPAKOV, S.Yu. MAKSIMOV and **I.A. RYABTSEV**

E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The results of works performed by the E.O. Paton Electric Welding Institute in the field of welding and surfacing using flux-cored wire are generalized.

Keywords: *electric arc welding, surfacing, low-alloyed steels, flux-cored wire, production of flux-cored wire*

The flux-cored wire is high-efficient electrode material allowing solution of wide range of tasks connected with manufacturing of welded structures at the modern level.

At the beginning of the 1950s I.I. Frumin offered the application of flux-cored wire for automatic submerged surfacing of mill rolls [1]. The production of surfacing flux-cored wire was organized at Magnitogorsk Metal Wares and Metallurgical Plant.

The idea of application of flux-cored wire as welding consumable appeared to be very fruitful. At the second half of the XX century the investigations of electric-physical, metallurgical and technological processes of welding and surfacing using flux-cored wire were carried out. As a result a large number of different types of flux-cored wires of different purpose was developed, technologies of welding and surfacing and also industrial equipment and technology of production of flux-cored wires were also developed and tested. The materials for welding and surfacing in shielding gases, materials without additional shielding (self-shielding flux-cored wires), flux-cored wires for underwater, arc (electric gas) and electric slag welding with a forced weld metal formation and also for desulphuration and alloying of metal melts were developed.

At present, welding and surfacing using flux-cored wire, widely applied in many countries of the world, are the most challenging arc processes for joining metals, restoration of products or to impart them the necessary properties.

In the present article the review of works of the staff of the E.O. Paton Electric Welding Institute in this field was made.

Development of welding using flux-cored wire. The first industrial samples of flux-cored wire were developed and tested under the industrial conditions in 1959–1961 [2–4]. Their successful tests in welding of different-purpose metal structures became the start of opening of a new effective direction in the field of mechanization and automation of the arc welding.

Since that period the integrated investigations were carried out at the E.O. Paton Electric Welding Institute, which resulted in the establishment of the fundamentals of metallurgy and technology of the flux-cored wire welding, development of new consumables and methods of welding with their application.

The investigation of peculiarities of processes of heat and mass exchange in heating and melting of powder compositions, development of reactions at welding speeds of heating and melting of steel sheath and flux core allowed determination of kinetics of proceeding of processes and offer methods of control of melting the composite material, development of reactions of gas evolution, oxidation, complex formation, which are accompanied in arc welding with a formation of interacting phases (metallic, gas, slag) [5–7].

The considerable volume of investigations combining calculation, experimental methods and mathematics modeling is devoted to the study of physical-metallurgical processes in the metal–gas–slag system. Basing on the obtained results the basic principles of design of compositions of the core of flux-cored wire for welding in shielding gases and without additional shielding were defined [8–10]. The establishment of regularities of absorption and desorption of gases in arc fusion welding gave possibility to elucidate the mechanism of porosity formation from the new positions. The study of hydrogen behavior in steels allowed determination of influence on the resistance to embrittlement (delayed fracture) of a number of factors, including distribution of hydrogen in metal, composition and structure of metal, stress, rate of deformations and temperature [5, 11–13].

The development of flux-cored wires for welding metal structures of steels of high strength required the conductance of profound investigations in the field of physical metals science of welded joints. In these investigations except of modern experimental methods (scanning electron microscopy, local X-ray spectral analysis, quantitative metallographic analysis and others) the methods of mathematical modeling were widely used [14–17].

The carried out investigations allowed the obtaining of new data about distribution of elements in the metal of welded joint, composition and distribution of non-metallic inclusions, developing the conceptions about effect of composition and structure of metal on micromechanisms of fracture and cold resistance. In the works [14, 18] new data about the influence of alloying, modifying and complex microalloying on the formation of structure components of weld metal and characteristics of mechanical properties of weld metal and welded joint are contained.

Important scientific information, having a large practical significance, was obtained as a result of investigations of stability of arc burning, melting and electrode metal transfer using modern information-measuring systems and computer processing of data about welding process [17, 19]. The investigations of thermodynamic properties of metal and slag in the process of their melting and crystallization served as a basis for control and optimization of technological in-process properties of flux-cored wires used in welding in different spatial positions with free and forced weld formation [20–22]. The methods were developed and works were carried out on evaluation of sanitary-hygienic characteristics of welding using flux-cored wires with different types of a core [23]. The E.O. Paton Electric Welding Institute with the participation of Ministry of Ferrous Metallurgy of the USSR worked out the national standard 26271 «Flux-cored wire for arc welding of carbon and low-alloy steels», which was put in force in 1984 and is acting nowadays (in the edition of 1992) at the territory of CIS countries [24]. The monographs [5, 25–30] are devoted to the problems of theory and practice of the flux-cored wire welding.

The priority of the E.O. Paton Electric Welding Institute in the development of flux-cored wires, methods of welding with their use and equipment is protected by more than 100 patents and Author's Certificates.

Welding using self-shielding flux-cored wires. The conditions of application of flux-cored wires without additional shielding from the air atmosphere define main requirements to their properties, in particular, to provide gas-slag protection of molten metal and application of metallurgical means of nitrogen binding into stable nitrides, to obtain favorable welding-technological characteristics, to provide high resistance to formation of cracks and pores, sufficient level of deoxidation and alloying of metal, which allows achieving the required level of mechanical properties of weld metal and welded joint. For non-alloyed carbon steels the required level of properties is provided due to application of tubular flux-cored wires with a flux core of a rutile-organic type [3, 31]. Such wires are produced since 1959, and till now they are applied mainly during repair-renovation welding and manufacturing of simple metal structures.

Tubular self-shielding wires with application of nitride-forming elements in the core (aluminium, titanium, zirconium) were developed in the 1960s [3, 32]. Considering the specifics of alloying their application was limited by certain classes of steels, which was determined by the difference in chemical composition of weld metal and base metal and possible unfavorable influence on the properties of welded joint metal. Later the compositions of wires with a core of fluoride and fluoride-oxide types were modified, which gave a possibility to obtain high values of mechanical properties of welded joints of carbon and low-alloyed steels of ordinary and increased strength.

A special place among the self-shielding flux-cored wires is occupied by the wires of a double-layer design, developed by the E.O. Paton Electric Welding Institute [4, 33, 34]. Such wires with a core of a carbon-fluoride type mainly provide reliable gas-slag protection of molten metal from the air and have no almost restrictions in the selection of type of the weld metal alloying. They are used in manufacturing of many welded different-purpose metal structures of low carbon and low-alloy steels of increased strength.

The welding using self-shielding flux-cored wires started its mass application since 1960 mainly in manufacturing and assembly of building, technological structures and equipment. Further the field of their application widened to other branches of industry and building. Mechanized welding using self-shielding flux-cored wires as a rule is performed by means of semi-automatic machines with a modernized feed mechanism (four- or two-roller of gear type). In site semi-automatic machines of a light type a wire of 1.6–2.0 mm diameter is used, and in stationary or semi-stationary (suspended) machines the wire of 2.4–3.0 mm diameter is used.

Welding using gas-shielding flux-cored wires. The development of welding using gas-shielding flux-cored wires was performed under the conditions of beginning of mass application of arc welding by silicon-manganese wire of solid section of the type Sv-08G2S and others in CO_2, and later — in gas mixtures. The conditions of their application, requirements to welding equipment, types-sizes of flux-cored wires of 1.0–2.0 mm diameter created no difficulties in mastering mechanized welding under the industrial conditions. The main tasks, solved during development of flux-cored wires, were focused on development of core types, alloying systems as applied to the class of steels being welded to achieve the best technological and engineering-economic values than in use of wires of solid section [26, 35–38]. The additional treatment of metal with a slag, control of welding-technological properties using a powder core, additional filler metal in a form of metallic constituents of a core provided such advantages in the application of gas-shielding flux-cored wires, as compared with wires of solid section, as high stability of welding process, small losses on spattering, considerable improvement of quality of welds deformation, high values of mechanical properties of weld metal, in particular plastic characteristics. The achieved increase of labor productivity amounts from 15 to 30 % [27, 39, 40].

In the last decade the development of automatic and robotic welding gave an impetus to the development of gas-shielding flux-cored wires with a metal core, whose content of non-metallic materials does not exceed 1 %. Such flux-cored wires are characterized by high speed and efficiency of melting (by 30–40 % higher than in welding using wire of solid section), due to their application the losses of electric energy are cut due to high fraction of filler electrode metal in the powder core [23, 41, 42]. The lack of a slag on the surface of a weld allows performing multilayer welding without cleaning from slag. High in-process properties in welding in gas mixtures are achieved due to fine-drop or spray electrode metal transfer. High level of values of mechanical properties (strength and tough-plasticity) was also obtained.

Gas-shielding flux-cored wires are applied in the most branches of industry where metal structures of carbon and low-alloy steels of increased and high strength are welded (in machine building, ship building, power engineering construction, etc.)

Specialized methods of welding using flux-cored wire. The specialized methods include methods of automatic welding, requiring application of special welding equipment, technologies and wires, which are characterized by peculiar properties in accordance with requirements specified to the conditions of welding and quality of welded joints. They include arc welding with a forced (electric gas) and semi-forced weld formation, automatic welding of circumferential welds with a pre-forming, welding using electric rivets and other [5, 43].

The electric arc welding of vertical butt joints of sheet structures (tanks, spans of bridges, ship sections on the bed, bodies of converters, blast furnaces, silo towers, etc.) foresees performance of process with a single — or two-sided forming of weld surface using movable (copper water-cooled shoe) or immovable means (ceramic or copper water-cooled backing) [44, 45].

Welding of horizontal welds in vertical plane is carried out using a pre-forming of a lateral surface of a weld pool by a special moving shoe, providing a «semi-forced» weld formation and required shape of its surface [5, 45, 46]. A large volume of a weld pool, necessity of obtaining of specific properties of a slag, forming the interlayer between a shoe and weld surface, absence of postweld heat treatment of a single-pass weld required creation of special flux-cored wires. For welding under site conditions at a designed position of the structures the self-shielding flux-cored wires of two-layer design were developed [9, 46].

The important step in the development of welding using flux-cored wire with a forced weld formation is the creation of method of welding, equipment and flux-cored wires to perform circumferential welds of butt joints of pipes in construction of main pipelines of large diameter [47–50]. The tasks of welding technology in all spatial positions providing stable high quality of welded joints of pipe steels of classes of strength from X50 to X80 were solved [29, 51]. The equipment and welding technology provide continuous monitoring of heat input and programmed control of welding process.

Flux-cored wires for underwater welding. The first half of the 1960s was characterized by beginning of intensive mastering of oil and gas deposits in Siberia and construction of main pipelines for transportation of gas to the European part of the USSR and countries of Europe. Considering a big number of water barriers on the way of lying down of pipelines and necessity to provide reliable service of the latter there appeared the demand for the development of technology of repair using underwater welding. Mechanical welding using solid wire in shielding gases and manual welding applied for this purpose did not provide the required quality of welded joints. According to the proposal of B.E. Paton the mechanized welding using flux-cored wires was decided to be used.

Since 1965 the fundamental investigations of metallurgical peculiarities of wet underwater welding and physical characteristics of the arc burning under water are carried out at the E.O. Paton Electric Welding Institute. The result of these works was creation in 1967 of flux-cored wire PPS-AN1 of rutile-ore-acid type for welding of non-alloyed structural steels at the depth of up to 20 m [52]. Metal of welds performed using mechanized welding by flux-cored wire as compared to manual welding was characterized by resistance against pores formation and had increased mechanical properties. New process allowed the increase of efficiency of welding, provide convenience and safety of work of a welder-diver, improve visibility of the zone of arc burning almost by 3 times.

Further, the investigations were directed on the determination of salinity of water, depth of works performance, search of the methods of optimization of gas-slag component of the charge of flux-cored wire and alloying systems [53–61], as a result the flux-cored wires were created for welding low-alloy steels with a yield strength of up to 400 MPa at the depth of up to 30 m, providing the weld metal with a required level of mechanical properties.

From the beginning of the 2000s the elements of structures of nuclear power stations began to be welded of stainless steels of the type 18-10. The application of developed flux-cored wires facilitated producing of welds, which according to the values of mechanical properties were superior to the welds produced on the air by electrodes of E-08Kh20N9G2B type, for example TsL-11 [62].

Since 1972 the E.O. Paton Electric Welding Institute carries out investigations on development of technology of mechanized arc cutting using flux-cored wire instead of manual electric oxygen cutting. The application of this method increased efficiency of the process and allowed refusing the supply of oxygen into the cutting zone, which is very important during performance of works under highly explosive conditions. The developed flux-cored wires allow performing technological and dividing cutting of low-alloy and stainless steels, aluminium, copper, titanium and their alloys of up to 40 mm thickness at the depths of up to 60 m [63, 64].

The practical application of developments of the E.O. Paton Electric Welding Institute began in 1969 during repair of water conduit of ∅1020 × 12 mm of steel 09G2, laid across the river Dnieper at the depth of 12 m [65]. In 1971 a repair of underwater part of the body of mid-size fishing trawler-refrigerator was for the first time performed using flux-cored wire [66]. Marine Register of the USSR allowed trawler to be admitted to the further navigation without docking. One of the examples of application of welding using flux-cored wire in building can be joining of four sections of floating platform «Prirazlomnaya» of 126 m length with overall length of three-pass fillet weld of about 1800 m afloat [67] and welding of underwater part of the supports of Podolsk-Voskresensk bridge across the Dnieper river in Kiev, the overall length of three-pass fillet weld was 5000 m.

The flux-cored wires for cutting were applied during works on cleaning offshore area from sunken ships, disassembling of underwater supports of stationary basements, performance of emergency-rescue operations. They were applied for the works on lifting submarine in the area of Petropavlovsk-Kamchatsky [68], repair of wharf walls in St. Petersburg, on the island Dikson, etc.

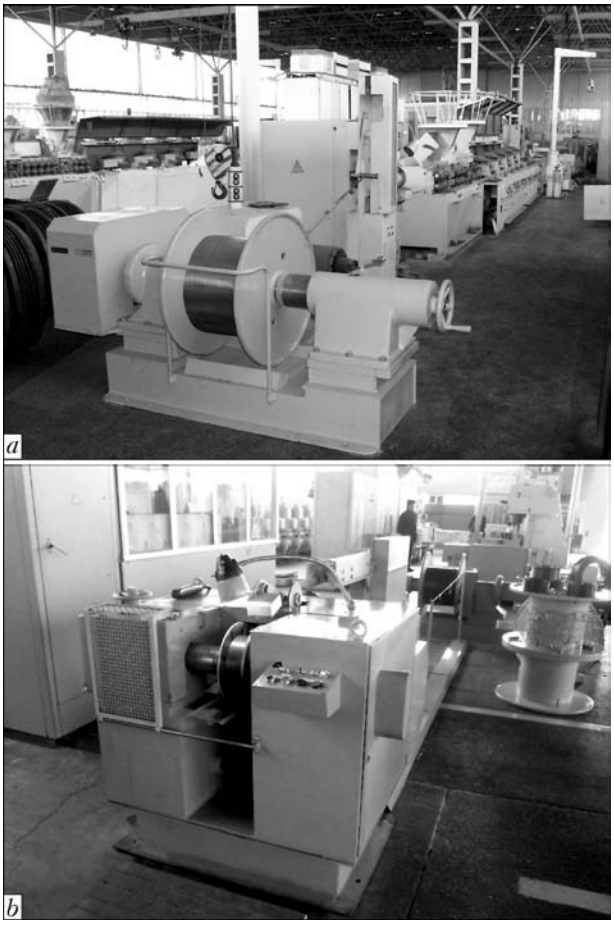
The technology of underwater wet welding and cutting using flux-cored wire developed at the E.O. Paton Electric Welding Institute is successfully applied in restoration of pipelines with maximal diameter of up to 1020 mm and working pressure of up to 5 MPa, liquidation of navigation and corrosion damages of ships afloat without further docking, repair of structure elements of hydro power stations, wharf walls, sea platforms, performance of emergency-rescue operations, etc.

The developments of the E.O. Paton Electric Welding Institute in the field of underwater wet welding using flux-cored wire are protected by 10 patents.

Flux-cored wires for electric arc surfacing. Nowadays the flux-cored wires are the most applied electrode material for automatic and mechanized electric arc surfacing of parts of machines and mechanisms in different branches of industry. As compared to the wires of large section the flux-cored wires provide great opportunities for alloying of deposited metal.

The first flux-cored wire PP-3Kh2V8 developed at the E.O. Paton Electric Welding Institute was designed for the surfacing of mill rolls. The composition of this wire was so successfully selected that it is still widely used in the industry under the designation PP-Np-35V9Kh3GSF.

The welding-technological properties of new surfacing electrode material were investigated, conditions of surfacing using wires providing quality deposited metal were developed [1, 69]. The first flux-cored wires were designed for surfacing under the flux.



Automatic line on manufacture of flux-cored wire (forming, filling, drawing) (*a*) and installation for coiling of flux-cored wire on framed spools K-300 (BS-300) (*b*)

As a result of investigations of interaction of slag melt with alloying elements [1, 69–73] the level of their oxidation or recovery from a slag was established which allowed calculating composition of a charge of flux-cored wires for surfacing with a sufficient level of accuracy.

In the works [1, 74–77] the mechanism of formation of crystalline cracks at surfacing and welding was investigated and measures of their prevention were offered. It was established that ledeburite low-melt eutectics forming during surfacing of high-carbon high-chromium steels at specified carbon content can cure discontinuities which are formed during solidification of these steels.

During surfacing of parts of low- and high-carbon steels it happens almost all the time to encounter the problem of cold crack formation. The most widely spread method of cold crack prevention is preheating of parts before surfacing and tempering after surfacing. To surface these parts without or with minimal heating the flux-cored wires PP-AN193, PP-AN195, PP-AN196 and PP-AN202 were developed at the E.O. Paton Electric Welding Institute providing the deposited metal with a high crack resistance [78].

Adding of additional mineral and metallic components to the charge of flux-cored wires gave possibility to struggle against such defect of the deposited metal as pores. To prevent hydrogen porosity I.I. Frumin offered to introduce tetrafluorine of alkaline metals into the core of flux-cored wire.

For mechanized arc surfacing using an open arc the gas- and slag forming components and different additions stabilizing the process of arc burning and preventing pores formation in surfaced metal are introduced into the charge of flux-cored wires. A number of self-shielding flux-cored wires for surfacing different wear-resistant alloys were developed [79, 80].

The investigations of peculiarities and character types of wear of parts of different machines and mechanisms were conducted and corresponding flux-cored wires were designed. To surface mill rolls and dies of different purpose a range of flux-cored wires was designed, such as PP-Np-35V9Kh3SF, PP-Np-25Kh5FMS, PP-AN132, PP-AN140, PP-AN147, PP-AN148, the application of which allows repeated restoration of worn-out parts. To restore and strengthen parts of metallurgical equipment the flux-cored wires PP-AN158, PP-AN159 and PP-AN147, providing the deposited metal of the type of high-chromium stainless steel with different hardness and wear resistance, were designed [81].

To surface parts operating under the conditions of abrasive wear with impact load of different intensity the flux-cored wires PP-AN125, PP-AN135, PP-AN170, PP-AN192, PP-AN197 and PP-AN105 are recommended.

To surface rods of mine hydrolinings of heading machines, pistons of hydraulic presses and other similar parts in manufacturing and restoration the flux-cored wire PP-AN165 was designed. A metal, deposited using this wire, is characterized by sufficiently high corrosion resistance in water-saline solutions and wear resistance in metal-against-metal friction. The application of surfacing allows excluding the ecologically harmful operation: chrome-plating of parts.

To surface shafts, axes, crane wheels and other parts operating under the conditions of friction of metal against metal with or without abrasive interlayer, it is recommended to apply flux-cored wires PP-AN120, PP-AN126, PP-AN194 and PP-AN198.

Till nowadays the E.O. Paton Electric Welding Institute develops and produces flux-core wire for submerged arc surfacing using open arc and also parts of different machines and mechanisms in shielding gases which are operated under conditions of almost all known kinds of wear [82]. The original compositions of flux-cored wires for surfacing are protected by five patents.

Creation of production of flux-cored wires. In the 1950s and beginning of the 1960s the flux-cored wires were manufactured at small areas equipped in shops of electrode production. The works on designing and organization of full-scale production of flux-cored wire and also development and realization of corresponding industrial technology were developed at the

E.O. Paton Electric Welding Institute attracting the organizations and enterprises with experience in creation of electrode productions, among which there were Institutes «Giprometiz» (Leningrad), NIIMetiz (Magnitogorsk), Alma-Ata Heavy Machine-Building Plant, organizations and enterprises of Minmontazhspetsstroj, etc. Head organization and coordinator of all works was the E.O. Paton Electric Welding Institute. The Institute performed the investigations of the technology of manufacture of flux-cored wire of different types. The study of combined deformation of solid and bulky bodies, load conditions at different schemes of treatment and organizing of technological process allowed developing the scientific and engineering bases of the industrial technology of manufacture. The designs of machines, devices and instruments for furnishing the production lines, in particular forming devices, charge batchers of continuous operation, units of degreasing, welding and coiling of steel strip, installations of continuous release of wire, devices of control and monitoring of filling wire with a charge.

The Design Bureau of the E.O. Paton Electric Welding Institute developed designs of specialized types of the equipment for forming of different flux-cored wires, batchers for filling steel sheath with a charge, devices for continuous release of flux-cored wire from the drawing mills, installations and outfit for degreasing of cold-rolled strip and other technological equipment. The pilot models of the equipment and main industrial machines were manufactured by the Pilot Plant of Welding Equipment of the E.O. Paton Electric Welding Institute. The developments of the Institute were transferred to the enterprises-manufacturers of the equipment. At the Alma-Ata Heavy Machine-Building Plant the industrial production of complete technological lines on manufacturing flux-cored wires was mastered. These production lines were used for productions being under construction (Nizhnedneprovskoe Metal Ware Production, Cherepovets Steel Rolling Plant, Dnepropetrovsk Plant of Welding Consumables, etc.). In 1978 the work of the staff of the E.O. Paton Electric Welding Institute on creation, organization of mass production and implementation of new materials (flux-cored wires) for mechanized welding, providing the increase of work efficiency and quality of welded structures was awarded the State prize of the USSR. The authors' staff included I.K. Pokhodnya, I.I. Frumin, A.M. Suptel, V.N. Shlepakov, V.F. Alter, and also the members of organizations and plants mentioned above.

In 1978 the Boiler-Welding Plant of Minchermet of the Ukr. SSR was transferred to the E.O. Paton Electric Welding Institute. In a short term the plant was considerably reconstructed and equipped with modern equipment. At present, the State Enterprise «Pilot Plant of Welding Consumables of the E.O. Paton Electric Welding Institute» is a leading enterprise in Ukraine on the production of welding consumables: electrodes, flux-cored wires (Figure), welding fluxes.

High level of developments of welding flux-cored wires, technologies of their manufacture and production equipment was recognized in many countries throughout the world. The transfer of documentation, delivery of equipment and mastering of technologies on the developments of the E.O. Paton Electric Welding Institute were performed on the base of license agreements and contracts with enterprises of France, Germany, USA, China, Japan, Argentina, etc.

The problems of theory and practice of manufacturing of flux-cored wires are generalized in the work [83]. The priority of developments of the E.O. Paton Electric Welding Institute in the field of technologies of manufacturing of wires and appropriate equipment is protected by more than 50 patents.

1. Frumin, I.I. (1952) Alloying of deposited metal in submerged-arc welding. *Avtomatich. Svarka*, 1(**22**), 3–19.
2. Pokhodnya, I.K., Suptel, A.M. (1959) Mechanized open arc flux-cored wire welding. *Ibid*., **11**, 3–12.
3. Pokhodnya, I.K., Shlepakov, V.N. (1961) Flux-cored wire with basic type core for semiautomatic open arc welding. *Ibid*., **7**, 87–88.
4. Pokhodnya, I.K. (1963) State-of-the-art and prospects of development of mechanized open arc flux-cored wire welding. In: *Proc. of 3rd Siberian Sci.-Techn. Conf. on Welding, Surfacing and Flame Treatment of Metals* (Krasnoyarsk, 1963).
5. Pokhodnya, I.K., Suptel, A.M., Shlepakov, V.N. (1972) *Flux-cored wire welding*. Kiev: Naukova Dumka.
6. Pokhodnya, I.K., Shlepakov, V.N. (1970) Effectiveness of metal protection in flux-cored wire welding. *Avtomatich. Svarka*, **2**, 10–12.
7. Shlepakov, V.N., Suprun, S.A., Kotelchuk, A.S. (1987) Kinetics of gas generation in flux-cored wire welding. *IIW Doc. XII-1046–87*.
8. Pokhodnya, I.K. (1972) *Gases in welds*. Moscow: Mashinostroenie.
9. Shlepakov, V.N. (1990) Kinetics of metal-gas interaction processes in flux-cored wire welding. In: *Problems of welding and special electrometallurgy*. Kiev: Naukova Dumka.
10. Pokhodnya, I.K., Demchenko, L.I., Shlepakov, V.N. et al. (1978) About mechanism of pore formation in welds. *Avtomatich. Svarka*, **6**, 1–5.
11. Pokhodnya, I.K., Demchenko, V.F., Demchenko, L.I. (1979) *Mathematical modeling of gas behavior in welds*. Kiev: Naukova Dumka.
12. Shlepakov, V.N., Giyuk, S.P. (1987) Application of slot bead-on-plate test for evaluation of resistance to cold cracking. *Avtomatich. Svarka*, **5**, 13–18.
13. Pokhodnya, I.K., Shvachko, V.I., Kotrechko, S.A. et al. (1998) New method for quantitative determination of susceptibility of steels to hydrogen embrittlement. *Fiz.-Khimich. Mekhanika Materialov*, **4**, 79–84.
14. Shlepakov, V.N., Shevchenko, G.A. (1986) Alloying of flux-cored wire core in welding of steels with different level of strength. In: *Proc. of 1st Int. School of CMEA Countries-Members on Flux-Cored Wire Welding. Metallurgical and Technological Problems of Flux-Cored Wire Welding* (Sofia, April 1986). Kiev: Naukova Dumka, 84–88.
15. Shlepakov, V.N., Kotelchuk, A.S. (1989) Evaluation of structural composition of low-alloy weld metal produced with flux-cored wire. In: *Coordination Center of CMEA Countries-Members on Problem of Evolution of Scientific Principles and Developments of New Technological Processes of Welding, Surfacing and Thermal Cutting of Different Materials and Alloys for Producing of Welded Structures and Effective Welding Consumables and Equipment*. Issue 1. Kiev: PWI, 7–10.
16. Shlepakov, V.N., Kotelchuk, A.S., Naumeiko, S.M. (2000) Effect of nitride-forming elements on composition and structure of low-alloyed weld metal. *The Paton Welding J*., **6**, 6–9.

17. Pokhodnya, I.K., Gorpenyuk, V.N., Milichenko, S.S. et al. (1990) *Metallurgy of arc welding: Processes in arc and melting of electrodes*. Ed. by I.K. Pokhodnya. Kiev: Naukova Dumka.
18. Pokhodnya, I.K., Orlov, L.N., Shevchenko, G.A. et al. (1985) Effect of alloying on mechanical properties of welds made with flux-cored wires. *Avtomatich. Svarka*, **7**, 8–11.
19. Shlepakov, V.N., Kotelchuk, A.S., Suprun, S.A. (1999) Identification of flux-cored wire composition on electric signals of arc welding. *Ibid*., **8**, 37–42.
20. Pokhodnya, I.K., Shlepakov, V.N., Orlov, L.N. (1983) Technological properties of slags in arc flux-cored wire welding with forced weld formation. In: *Coordination Center of CMEA Countries-Members on Problem of Evolution of Scientific Principles and Developments of New Technological Processes of Welding, Surfacing and Thermal Cutting of Different Materials and Alloys for Producing of Welded Structures and Effective Welding Consumables and Equipment*. Issue 1. Kiev: PWI, 94–97.
21. Shlepakov, V.N., Naumejko, S.M. (2001) Effect of surface tension of welding slags of salt-oxide system on characteristics of welding-technological properties of self-shielding flux-cored wire. *The Paton Welding J*., **11**, 21–24.
22. Shlepakov, V.N., Bilinets, A.V. (2003) Flux-cored wires with metal core for gas-shielded welding. *Ibid*., **3**, 44–45.
23. Pokhodnya, I.K., Shlepakov, V.N., Suprun, S.A. et al. (1983) Procedure of primary sanitary-hygienic evaluation of flux-cored wires. In: *Coordination Center of CMEA Countries-Members on Problem of Evolution of Scientific Principles and Developments of New Technological Processes of Welding, Surfacing and Thermal Cutting of Different Materials and Alloys for Producing of Welded Structures and Effective Welding Consumables and Equipment*. Issue 1. Kiev: PWI, 28.
24. *GOST 26271–84*: Flux-cored wire for arc welding of carbon and low-alloy steels. General specifications. Introd. 07.09.84.
25. Pokhodnya, I.K., Yavdoshchin, I.R., Shvachko, V.I. et al. (2004) *Metallurgy of arc welding. Interaction of gases with metals*. Ed. by I.K. Pokhodnya. Kiev: Naukova Dumka.
26. Pokhodnya, I.K., Suptel, A.M., Shlepakov, V.N. (1973) *Arc flux-cored wire welding*. Moscow: Mashinostroenie.
27. Pokhodnya, I.K., Suptel, A.M., Shlepakov, V.N. et al. (1975) *Flux-cored wire welding of parts and assemblies of construction and road machines*. Series 5: Technology, economics, organization of production. TsNIITEstrojmash.
28. Pokhodnya, I.K., Suptel, A.M., Shlepakov, V.N. et al. (1980) *Flux-cored wires for electric arc welding*: Catalogue-Refer. Book. Ed. by I.K. Pokhodnya. Kiev: Naukova Dumka.
29. Pokhodnya, I.K., Shejnkin, M.Z., Shlepakov, V.N. et al. (1987) *Position arc welding of main pipelines*. Moscow: Nedra.
30. Pokhodnya, I.K., Shlepakov, V.N. (1995) *Welding with flux-cored wire*. Series Welding and Surfacing Rev. Ed. by B.E. Paton. Vol. 4, Pt 4. Harwood AP.
31. Suptel, A.M., Pokhodnya, I.K. (1969) *Flux-cored wire of rutile type for open arc welding*: Guidelines on application. Kiev: Znanie.
32. Pokhodnya, I.K., Shlepakov, V.N. (1964) Flux-cored wire PP-AN3 for welding of low-carbon and low-alloy steels on higher currents. *Avtomatich. Svarka*, **1**, 61–65.
33. Pokhodnya, I.K., Shlepakov, V.N. (1967) Flux-cored wire for open arc welding of low-carbon and low-alloy steels. *Svarochn. Proizvodstvo*, **2**, 21–22.
34. Pokhodnya, I.K., Shlepakov, V.N. (1969) *Flux-cored wire of carbonate-fluorite type for open arc welding*: Guidelines on application. Kiev: Znanie.
35. Pokhodnya, I.K. (1967) Flux-cored wire welding and prospects of its development. *Svarochn. Proizvodstvo*, **11**, 43–45.
36. Pokhodnya, I.K., Shlepakov, V.N., Suprun, S.A. (1973) Flux-cored wire PP-AN9 with improved hygienic characteristics. *Ibid*., **1**, 48–49.
37. Pokhodnya, I.K., Kasatkin, B.S., Musiyachenko, V.F. et al. (1984) *Flux-cored-wire PP-AN54 for welding of high-strength low-alloy steels:*/L 58/1461. Kiev: PWI.
38. Shlepakov, V.N., Kotelchuk, A.S., Naumejko, S.M. et al. (2005) Influence of the composition of flux-cored wire core and shielding gas on the stability of arc welding process. *The Paton Welding J*., **6**, 16–20.
39. Pokhodnya, I.K., Golovko, V.N. (1974) High productive flux-cored wire for CO_2 welding. *Avtomatich. Svarka.*, **7**, 66–70.
40. Pokhodnya, I.K., Golovko, V.N., Suprun, S.A. et al. (1978) Peculiarities of CO_2 flux-cored wire welding process. In: *Coordination Center of CMEA Countries-Members on Problem of Evolution of Scientific Principles and Developments of New Technological Processes of Welding, Surfacing and Thermal Cutting of Different Materials and Alloys for Producing of Welded Structures and Effective Welding Consumables and Equipment*. Issue 1. Kiev: PWI, 109–116.
41. Shlepakov, V.N., Gavrilyuk, Yu.A., Kotelchuk, A.S. et al. (2010) Principles of formation of flux-cored wire compositions with high welding rate. In: *Abstr. of 5th Int. Conf. on Welding Consumables. Technologies. Production. Quality. Competitiveness* (Artemovsk, 7–11 June, 2010). Kiev, 172–178.
42. Shlepakov, V.N., Gavrilyuk, Yu.A., Kotelchuk, A.S. (2010) State-of-the-art of development and application of flux-cored wires for welding of carbon and low-alloyed steels. *The Paton Welding J*., **3**, 38–42.
43. Pokhodnya, I.K., Dubovetsky, V.Ya., Shlepakov, V.N. et al. (1966) Arc welding of vertical welds with forced formation. *Avtomatich. Svarka*, **11**, 67–70.
44. Pokhodnya, I.K., Lebedev, B.F., Shlepakov, V.N. et al. (1981) Automatic self-shielded flux-cored wire welding of vertical welds in operational metal structures of nuclear power plants. *Energomashinostroenie*, **5**, 34–36.
45. Pokhodnya, I.K., Suprun, S.A., Kazatsky, A.I. et al. (1987) Prospects of application of self-shielded flux-cored wire welding in shipbuilding. *Sudostroenie*, **5**, 24–26.
46. Shlepakov, V.N., Suprun, S.A., Kotelchuk, A.S. (1990) Estimating of the characteristics of flux-cored wire welding under the wind flow effect. In: *Proc. of Int. Conf. on Welding under Extreme Conditions* (Helsinki, Finland, Sept. 4, 1989). Oxford, New York: Pergamon Press, 171–179.
47. Pochodnja, I.K., Shlepakov, V.N., Iljuschenko, W.M. et al. (1995) *Hochleistungsschweissen von Vertikalnahten mit Zwangsformung. Sondertagung «Schweissen in Schiff- und Metallbau» mit Vorkolloqium* (Rostok, Mai 4–5, 1995). Duesseldorf: DVS, 23.
48. Pokhodnya, I.K., Shlepakov, V.N., Dubovetsky, V.Ya. et al. (1983) Resource-saving technology of automatic welding of main pipelines with flux-cored wire and at forced weld formation. *IIW Doc. XI-412–83*.
49. Shlepakov, V.N. (1998) Flux-cored wire automatic electric arc welding of position butt joints of pipelines. In: *Proc. of Int. Conf. on Welding of Pipelines* (Istanbul, May 12–13, 1998), 1–8.
50. Paton, B.E., Pokhodnya, I.K., Dubovetsky, V.Ya. et al. (1981) Automatic self-shielded flux-cored wire welding of position butt joints of large diameter. *Stroitelstvo Truboprovodov*, **2**, 22–24.
51. Pokhodnya, I.K., Shlepakov, V.N., Dubovetskii, V.Ya. et al. (1983) Resources-saving technology of position automatic flux-cored wire welding of gas pipelines with a forced weld formation. In: *Proc. of Int. Conf. on Welding in Energy Related Projects* (Toronto, Sept. 20–21, 1983), 133–139.
52. Savich, I.M. (1969) Underwater flux-cored wire welding. *Avtomatich. Svarka*, **10**, 70.
53. Kononenko, V.Ya. (1980) Influence of carbon, silicon and manganese on technological properties and impact toughness of underwater-welded metal. In: *Underwater welding and cutting of metals*. Ed. by A.E. Asnis. Kiev: PWI.
54. Asnis, A.E., Ignatushenko, A.A., Dyachenko, Yu.V. (1983) Method of decrease of hydrogen content in HAZ during mechanized underwater welding. *Avtomatich. Svarka*, **8**, 1–4.
55. Ignatushenko, A.A., Denisenko, A.V., Djachenko, Yu.V. (1983) Mechanized underwater welding using austenitic consumables. In: *Underwater welding*. Oxford: Pergamon Press, 227–236.
56. Savich, I.M., Kononenko, V.Ya., Gusachenko, A.I. (1984) Structure of weld metal and near-weld zone in welding under the water of different salinity. *Avtomatich. Svarka*, **4**, 50–52.
57. Gusachenko, A.I., Kononenko, V.Ya. (1989) Automatic underwater flux-cored wire welding of low-alloy steels. *Ibid*., **7**, 32–34.
58. Gretsky, Yu.Ya., Maksimov, S.Yu. (1995) Effect of nickel on structure and properties of welds in underwater flux-cored wire welding. *Ibid*., **8**, 56–57.
59. Yushchenko, K.A., Gretskii, Yu.A., Maksimov, S.Yu. (1998) Study of physico-metallurgical peculiarities of wet arc welding of structural steels. In: *Underwater wet welding and cutting*. Woodhead Publ., 6–29.
60. Maksimov, S.Yu., Savich, I.M., Zakharov, S.M. et al. (2003) Structure and properties of the metal deposited under the water by flux-cored wire with a nickel sheath. *The Paton Welding J*., **4**, 18–21.

61. Gretsky, Yu.Ya., Maksimov, S.Yu. (2004) Increase in stability of arc, burning under water, in flux-cored wire welding. *Ibid.*, **2**, 9–12.
62. Yushchenko, K.A., Kakhovsky, Yu.M., Fadeeva, G.V. et al. (2006) Self-shielded flux-cored wire for underwater welding of high-alloy steels of 12Kh18N10T type. In: *Problems of service life and security of structures, constructions and machines:* Coll. of papers on results received in 2004–2006. Kyiv: PWI.
63. Danchenko, M.E., Savich, I.M., Nefedov, Yu.N. (1988) Underwater arc cutting with flux-cored wire. *Avtomatich. Svarka*, **4**, 59–61.
64. Gretsky, Yu.Ya., Nefedov, Yu.N. (1993) *Technology of mechanized underwater arc cutting with flux-cored wire of carbon and alloy steels*. Kiev: PWI.
65. Kononenko, V.Ya., Rybchenkov, A.G. (1994) Experience of mechanized wet welding with self-shielded flux-cored wires in underwater repair of gas- and oil pipelines. *Avtomatich. Svarka*, **9/10**, 29–32.
66. Kononenko, V.Ya., Gritsaj, P.M., Semenkin, V.I. (1994) Application of mechanized wet welding in repair of ship hulls. *Ibid.*, **12**, 35–38.
67. Kononenko, V.Ya. (2005) Application of the technology of mechanized underwater welding in construction of offshore ice-resistant platform «Prirazlomnaya». *The Paton Welding J.*, **12**, 47.
68. Savich, I.M., Maksimov, S.Yu. (2001) Application of mechanized cutting in pulling of submarine. *Avtomatich. Svarka*, **2**, 59–60.
69. Frumin, I.I. (1961) *Automatic electric arc surfacing*. Kharkov: Metallurgizdat.
70. Podgaetsky, V.V. (1953) Reactions in arc atmosphere during submerged-arc welding. *Avtomatich. Svarka*, **1**, 10–17.
71. Pokhodnya, I.K. (1955) Interaction of slag with metal in arc and electroslag surfacing of high-chromium ledeburite steels. *Ibid.*, **5**, 33–46.
72. Frumin, I.I., Rabkin, D.M., Podgaetsky, V.V. et al. (1956) Low-silicon fluxes for automatic welding and surfacing. *Ibid.*, **1**, 3–20.
73. Frumin, I.I. (1958) About achievement of equilibrium between slag and metal in welding and surfacing. *Ibid.*, **1**, 3–13.
74. Frumin, I.I. (1957) On mechanism of solidification cracks in welding and surfacing. *Ibid.*, **1**, 4–8.
75. Pokhodnya, I.K. (1955) About effect of cooling rate on formation of solidification cracks. *Ibid.*, **6**, 64–73.
76. Pokhodnya, I.K. (1956) About effect of chemical composition of iron-chrome-carbon alloys on formation of solidification cracks. *Ibid.*, **6**, 55–63.
77. Pokhodnya, I.K. (1959) Hot (solidification) cracks in surfacing of high-carbon high-chromium ledeburite steels. In: *Hot cracks in welded joints, ingots and casts*. Moscow: AN SSSR.
78. Kondratiev, I.A., Ryabtsev, I.A., Chernyak, Ya.P. (2006) Flux-cored wire for surfacing of maraging steel layer. *The Paton Welding J.*, **4**, 41–43.
79. Yuzvenko, Yu.A. (1972) Flux-cored wire for surfacing. *Avtomatich. Svarka*, **5**, 67–71.
80. Yuzvenko, Yu.A., Kirilyuk, G.A. (1973) *Flux-cored wire surfacing*. Moscow: Mashinostroenie.
81. Ryabtsev, I.A., Kondratiev, I.A. (1999) *Mechanized electric arc surfacing of metallurgical equipment parts*. Kiev: Ekotekhnologiya.
82. Ryabtsev, I.A. (2004) *Surfacing of machine and mechanism parts*. Kiev: Ekotekhnologiya.
83. Pokhodnya, I.K., Alter, V.F., Shlepakov, V.N. et al. (1980) *Production of flux-cored wire*: Manual for institutes of higher education. Kiev: Vyshcha Shkola.

JAPANESE WELDING FABRICATION DURING 2009 ECONOMIC CRISIS

O.K. MAKOVETSKAYA
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper presents statistical data characterizing the condition of the Japanese market of welding equipment at the final stage of the world financial-economic crisis of 2009.

Keywords: *welding fabrication, market of equipment and materials, action plan, priority areas*

Market of the main structural materials. In 2009 the world financial crisis resulted in a considerable reduction of production of the main structural materials in Japan. Compared to 2008, production of raw steel was reduced to 26.3 % and was equal to 87.5 mln t. This is the lowest level of productions since 1969. Output of all kinds of finished steel products was also greatly reduced. Table 1 gives the data on hot-rolled stock production for the period of 2007–2009 [1].

Metal working industries reduced their orders by 30 % (to 37.5 mln t). Steel consumption in construction decreased by 26.1 % (to 9.6 mln t), in mechanical engineering by 29.8 % (to 18.2 mln t), and in shipbuilding by 2.8 % (to 5.5 mln t). Automotive companies reduced their orders for steel products to the greatest degree (by 35.5 %, to 7.3 mln t). As predicted by JFF Holdings, in 2010 an increase of the volume of orders in automotive and mechanical engineering industries is anticipated.

Production of primary aluminium in 2009 decreased by 23.2 % (to 5.1 thou t), secondary aluminium — by 36.9 % (to 666.0 thou t), aluminium rolled stock — by 21.4 % (to 1.062.8 thou t), and that of extruded sections — by 24.2 % (to 673.1 thou t). Domestic consumption of aluminium in 2009 was equal to 3250.1 thou t (by 23.4 % less than in 2008). Table 2 gives the pattern of consumption of aluminium rolled stock and extruded sections in Japan by individual industries and in construction [2].

Welding consumables market. Welding consumables market in Japan is closely related to structural metal market, particularly, that of steel [3]. Reduced consumption of finished steel products by the main metal working industries led to a considerable reduction of welding consumables market. For instance, consumption of welding consumables in shipbuilding

Table 1. Hot rolled stock production, thou t

Hot rolled stock	2007	2008	2009	2009/2008, %
Conventional steel	86,704.4	84,299.5	63,487.9	75.3
Special	21,498.2	21,782.1	13,247.1	60.8

was reduced by 10.9 %, as well as consumption of welding consumables in automotive and bridge construction, industrial mechanical engineering, and in a number of other industries, that resulted in decrease of total production volume in 2009 by almost 30 %, compared to 2008, and it reaching the minimum level for the last 20 years. This led to reduction of welding consumable manufacture by individual product types (from 9 to 44 %).

Volume and pattern of domestic consumption of the main groups of welding consumables in 2009 are shown in Table 3 [4].

Reduction of the total volume of welding consumable consumption affected the pattern of consumption of individual types of welding consumables. Flux-cored wire consumption decreased to the smallest degree (by 9 %), and its share in the pattern of consumption rose to 38.7 %, becoming commensurate with the fraction of solid wire application, the volume of application of which dropped to the greatest degree (44.2 %). Volumes of foreign trade in welding consumables were also reduced. Import of welding consumables decreased by 40.0 % (33.62 thou t); solid wire import — by 56.6 % (to 11.5 thou t), that of coated electrodes — by 20.4 % (to 1.58 thou t). On the other hand, flux-cored wire import rose by 4 %, and in 2009 amounted to 14.4 thou t, while export of welding consumables decreased by 31.5 % (39.9 thou t).

Table 2. Industrial pattern of consumption of aluminium rolled stock and extruded sections, thou t

Industry	Rolled stock		Extruded sections	
	2009	2009/2008, %	2009	2009/2008, %
Food	428.6	−1.1	0.9	−18.9
Dishware manufacture	2.7	−6.5	1.2	−35.5
Foil	113.1	−21.8	–	–
Metal products	76.7	−20.4	18.9	−25.7
Electric power	76.9	−29.0	31.1	−5.7
Transportation	118.8	−37.7	104.3	−36.6
Industrial mechanical engineering	19.1	−47.4	40.4	−44.8
Construction	40.6	−12.2	426.2	−17.1
Other	40.4	−47.3	38.4	−32.4
Total	916.9	−19.3	661.3	−24.0

By estimates of Japanese experts, in 2010 no significant growth of production is anticipated in metalworking industry and in construction, so that welding consumables demand will remain practically on 2009 level. In 2010 the volume of welding consumable manufacture is predicted to increase by 2.1 % (257.6 thou t). Welding consumable export in 2010 will increase by 2.0 % (up to 36.7 thou t), and import — by 2.3 % (up to 34.38 thou t).

Welding consumable market. 2009 marked a considerable decline of welding equipment manufacture: quantity of manufactured welding equipment was reduced by 60 % (by almost 50 % in terms of cost). Table 4 gives the data on the volume of welding equipment manufacture in Japan in 2009/2008, as well as 2010 prediction [5].

Volume of arc welding equipment is equal to about 95 % of all welding equipment produced in Japan. In 2009 production of standard automatic and semi-automatic equipment for arc welding decreased by 66.7 % (22,100 pcs). Almost 90 % of equipment of the above type are MAG welding machines. Industry's demand for this type of equipment is very high, but in connection with production decline in automotive, shipbuilding and some other industries, investments into this sphere of welding fabrication have been practically frozen. Shipbuilding was an exception, having had a sufficient backlog of orders. However, it does not seem possible to stabilize the situation by the efforts of just this industry.

Despite a considerable setback in production of automatic and semi-automatic equipment, output of new generation welding equipment with digital control systems is rising continuously in this segment. At present in construction and in a number of other industries producing welded structures, traditional welding equipment is being replaced by digital equipment: of every 10 units of equipment four are replaced by equipment fitted with power sources with digital control systems. About 10 % of digital power source output is exported to the countries of North America, Europe and Asia.

According to 2010 forecast, a growth of manufacturing of standard automatic and semi-automatic equipment by 12 % in terms of quantity is anticipated that will amount to 24,700 pcs, and in terms of cost, an increase of sales is anticipated on the level of 15 % against 2009 level.

Manufacturing of resistance welding machines in 2009 decreased by 65.4 % in terms of quantity, and by 55.3 % in terms of cost. In 2010 a 13.8 % (3300 pcs) growth of manufacturing of these machines is anticipated, that is associated with the predicted increase of export in automotive sector in 2010.

Japan is the world leader in the field of manufacture of industrial robots and production automation based on welding process robotization. Welding robots make up about 20 % of all the robots produced in the

Table 3. Volume and pattern of domestic consumption of welding consumables

Type of welding consumable	2008		2009		2009/2008, %	2010 (prediction)	
	thou t	%	thou t	%		thou t	%
Coated electrodes	40.6	11.4	30.6	12.1	75.4	29.4	11.5
Wires:							
for submerged-arc welding + flux	40.2	11.3	28.9	11.4	71.9	31.3	12.3
thin solid	167.5	46.7	93.4	37.0	55.8	95.5	38.2
for TIG welding, gas welding, cutting, etc.	2.1	0.6	1.9	0.8	90.5	1.9	0.8
Flux-cored wire	107.5	30.0	97.4	38.7	90.9	99.5	37.2
Total	358.4	100.0	252.2	100.0	70.4	257.6	100.0

country, of which the absolute majority are robots used for traditional technologies of arc and resistance welding, and more than 70 % of them are used in automotive industry.

Proceeding from statistical data, during the first half of 2009 reduction of production volume of welding robots in terms of cost, compared to a similar period of 2008, amounted to more than 57 %. Domestic consumption of robots during this period was reduced by almost 55 %, and export — by 60 %. Table 5 gives the data on cost fraction of welding robot manufacture in 2008, as well as in the first half of 2009. Decline in welding robot manufacture affected the resistance welding sector to a greater degree [6].

The above-said leads to the conclusion that the world financial-economic crisis had a strong influence on Japanese economy, including metalworking industries and welding fabrication. The volume of welding equipment manufacture decreased from 30 to 60 % by individual product types.

In response to the crisis, the welding industry, research organizations and professional associations of Japan developed specific action plans both on the level of individual firms and organizations, and the national long-term (up to 20 years) programs of welding fabrication development. Japanese manufacturers believe that the main priority for the near-term is maintaining reasonable market prices and return on investment. To increase the turnout in welding equipment market, Japanese specialists proposed action programs «New cost» and «Three in one», under which it is intended to perform optimization of welding fabrication, eliminating considerable overheads, optimisation of technological processes of welding, as well as development of new high-quality products. The efforts of manufacturers, dealers and users of welding equipment should be coordinated, domestic sales should be increased by studying the needs of welding structure fabricators, particularly of small and medium companies.

Japan is trying to become world leader, «have its own face» also in the field of welding and joining technologies. With this purpose the Japanese welding society proposed a new philosophy of research performance in the sector of welding and manufacturing of welding equipment — self-made concept. On the government level as part of activities of the Japan Welding Society, programs of research in the field of specific welding and joining technologies for the next 20 years have been developed, as well as strategic goals of welding technology development in individ-

Table 4. Indices of welding equipment fabrication in Japan

Equipment	2008, pcs (bln JPY)	2009, pcs (bln JPY)	2009/2008, % (bln JPY)	2010 prediction, pcs (bln JPY)
All arc welding equipment	128,100 (39,797)	50,900 (20,790)	39.7 (52.2)	56,800 (21,550)
Including:				
rotary converters	22,200 (6324)	7900 (2590)	35.6 (41.0)	9500 (3100)
automatic and semi-automatic machines	66,400 (21,847)	22,100 (8200)	33.3 (37.5)	24,700 (9430)
power sources, etc.	39,500 (11,626)	20,900 (10,000)	52.9 (86.0)	22,600 (9020)
Resistance welding machines, total	8400 (9841)	2900 (4400)	34.6 (44.7)	3300 (4900)
Total	136,500 (49,638)	53,800 (25,190)	39.4 (50.7)	60,100 (26,450)

Table 5. Cost fraction (mln JPY) of manufacture, domestic supplies and export of industrial robots and manipulators for welding in the first half of 2008 and 2009

Applications	January–June 2008			January–June 2009			January–June 2009/ January–June 2008, %		
	Domestic consumption	Export	Total	Domestic consumption	Export	Total	Domestic consumption	Export	Total
All industrial robots	103,896	200,723	304,598	51,200	58,586	109,786	49.3	29.2	36.0
For the following welding processes, in particular:	26,552	30,203	56,755	12,101	12,102	24,203	45.6	40.1	42.6
arc	14,791	13,385	28,176	7363	6234	13,957	49.8	46.6	49.5
resistance	11,702	16,803	28,506	4701	5864	10,565	40.2	34.9	37.1
laser	15	10	25	11	–	11	73.3	–	44.0
other	44	5	49	27	4	31	61.4	80.0	63.3

ual industries. Main directions of research and industrial production sectors were outlined, which will be the main consumers of the developed welding and joining technologies. Priority directions of research include welded structures, welding processes, welding metallurgy, fatigue strength of welded structures, welding arc physics, beam treatment, lightweight structure development, microwelding, joining over the interface. Fields of shipbuilding and bridge construction, nuclear engineering, chemical industry, high pressure vessel manufacture were named as priority areas for the Japanese welding fabrication. Under the program it is planned to develop and introduce a systems approach in performance of research and development, and creation of new product samples. It is intended to produce welded structures and products with a new level of properties based on the compiled intelligent databanks that will enable designing welding consumables and welded structure characteristics, as well as welding technology and optimizing it. The proposed systems approach will enable standardization of the process of welding and joining on a qualitatively new level.

1. The Japan iron and steel federation. *http://www.jisf.or.jp*
2. Japan *aluminium association. http://www.aluminium.or.jp*
3. Bernadsky, V.N., Makovetskaya, O.K. (2009) Japan welding production. Specifics of modern development. *Svarochn. Proizvodstvo*, **10**, 42–50.
4. (2010) Welding consumables. *The Japan Welding News,* Winter Issue, 14(**50**), 1–2.
5. Welding machines. *Ibid*., 3–4.
6. Japan robot association. *http://www/jara.jp/e/*

DEPOSITION OF TiO_2 COATINGS BY HIGH-VELOCITY AIR-GAS SUSPENSION PLASMA SPRAYING

Yu.S. BORISOV[1], **A.L. BORISOVA**[1], **M.V. KOLOMYTSEV**[1], **E.K. KUZMICH-YANCHUK**[1], **A.Yu. TUNIK**[1], **O.N. KOZARUK**[2] and **V.A. YAROSHENKO**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]Research and Production Company «Micron Ltd.», Cherkassy, Ukraine

Experiments on deposition of TiO_2 coatings by using the TiO_2 water suspension containing 15 wt.% of the nanosized TiO_2 particles as a spraying material were carried out. The experiments were conducted by the high-velocity air-gas plasma spraying method (unit «Kiev-S»). Thickness of the deposited coatings was 80 ± 12 μm. The anatase/rutile content ratio changed during the spraying process from 79/21 (in powder) to 31/69 (in coating).

Keywords: *titanium dioxide, suspension, coating, plasma spraying, phase composition, structure*

One of the trends in development of the thermal spraying methods is the use of suspensions consisting of a liquid phase and finely dispersed (up to nanosize) powder as a spraying material. This allows replacement of air transport of powders to the spraying zone by liquid transport and avoidance of such problems as poor flowability and sensitivity of finely dispersed powders to agglomeration. Also, this makes it possible to form thin (1 μm thick or thinner) layers of the spraying material, including with the nanosized structure [1, 2]. The experience accumulated up to now includes experimental studies on deposition of oxide (Al_2O_3–TiO_2, ZrO_2, TiO_2) and carbide (WC–Co) coatings [2]. Suspensions are sprayed by the plasma and flame spraying technologies [2] by using water and ethanol as a liquid medium.

The focus of researchers has been on deposition of coatings by using the TiO_2 suspension, which is associated with photocatalytic properties of the TiO_2 coatings and their high potential for purification of air (e.g. from acetylaldehyde, ammonia, nitrogen oxides etc.) and water (from phenols etc.) [3, 4]. It has been shown that the nanocrystalline porous TiO_2 layer forming in plasma spraying of the TiO_2 suspension can be used for manufacture of a new type of solar cells (Graetzel cells) characterised by an increased efficiency (10–11 %) [5].

The water suspension containing 15 wt.% of the nanosized TiO_2 particles was used as a source material for deposition of the TiO_2 coatings.

As revealed by X-ray phase analysis, the TiO_2 powder (Figure 1), which is a component of the suspension, contains 79 wt.% anatase (tetragonal lattice with elementary cell sizes a = 0.3798 and c = 0.9532 nm) and 21 wt.% rutile (tetragonal lattice with elementary cell sizes a = 0.4595 and c = 0.2955 nm).

The regions of coherent scattering for anatase and rutile estimated at 7.6 and 24 nm, respectively, are indicative of nanodispersion of the initial particles.

Examination of the powder with a scanning electron microscope shows that the TiO_2 particles with a size of about 100–200 nm form conglomerates up to 1.0–1.5 μm in size.

To provide uniform distribution of the powder particles in the suspension, prior to spraying it was subjected to ultrasonic treatment for 5–7 min by using the UZ-DN-A unit. It was enough to preserve homogeneity of the suspension for several hours and provide its uniform feed to the plasma jet.

The TiO_2 suspension coatings were deposited by the high-velocity air-gas plasma spraying by using the upgraded «Kiev-S» unit.

The suspension was transported to the plasma jet with an air compressor, which created the backup pressure by means of the compressed air in the suspension vessel. Prior to ignition of the plasma jet, the compressed air was fed under a low pressure via a separate line to the injector to blow the suspension feed nozzle. After ignition of the plasma jet and reaching the spraying mode by the plasmatron the suspension started to be fed from a low pressure of the backup

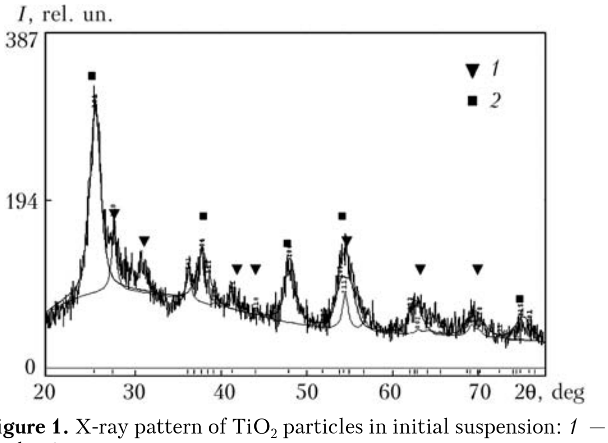


Figure 1. X-ray pattern of TiO_2 particles in initial suspension: *1* — rutile; *2* — anatase

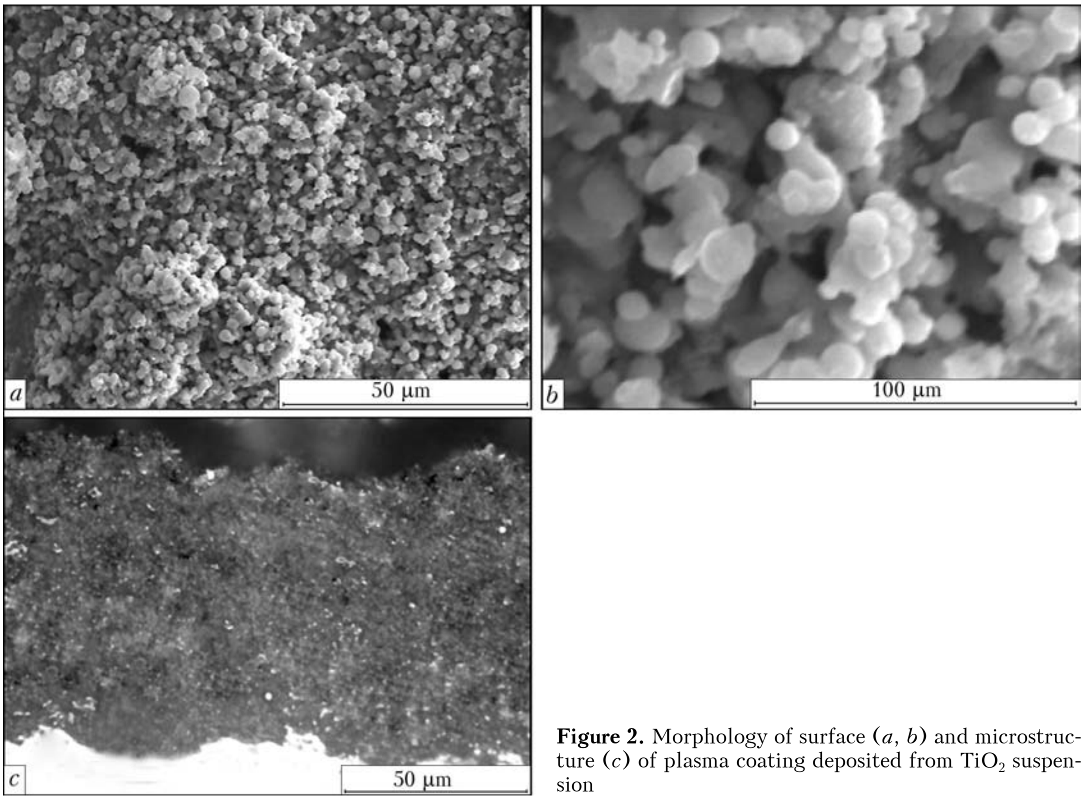


Figure 2. Morphology of surface (*a*, *b*) and microstructure (*c*) of plasma coating deposited from TiO_2 suspension

gas and, simultaneously, feeding of the compressed air for blowing the injector nozzle was stopped. Then the backup gas pressure mode was reached, when the suspension jet was fully mixed with the plasma jet causing no violation of its axial stability. The suspension was fed to under the plasmatron nozzle section at a distance of 10 mm and angle of 10° in a direction opposite to that of the plasma jet. Diameter of the injector nozzle was 0.5 mm.

Technological parameters of the unit after reaching the spraying mode were as follows: I = 250 A, U = = 290 V, L = 120 mm, plasma gas flow rate — 18 m^3/h, and backup gas (air) pressure — 3.5 atm. The coatings were deposited on the carbon steel samples 16 × 16 × 3 mm in size.

Homogeneous coatings, uniform through thickness, crack-free and having no separation from the substrate, were produced as a result of the experiment (Figure 2). Thickness of the coatings was 80 ± 12 μm. They had a finely dispersed structure formed from rounded coagulated particles 6–17 μm in size. The coatings had low microhardness, i.e. 1420 ± 300 MPa, this being attributable to their low cohesion strength.

During spraying, heating of the powder by the plasma jet caused structural-phase transformations in titanium dioxide, leading to a change in proportion of its two main modifications — rutile and anatase. Thus, the content of anatase decreased to 31 wt.%, and that of rutile grew to 69 wt.%, compared to the initial powders with the anatase and rutile contents of 79 and 21 wt.%, respectively (see Figure 1). With this the lattice parameters of both phases changed but insignificantly: a = 0.4593 and c = 0.2942 nm for rutile, and a = 0.3776 and c = 0.9491 nm for anatase. Anatase is a low-temperature modification of TiO_2. In heating within a temperature range of 699–915 °C it transforms into rutile [6]. This explains increase in the rutile content of a coating during plasma spraying, compared to the initial powder.

Therefore, it was established that high-velocity plasma spraying of water suspension with the TiO_2 powder can provide formation of coatings up to 80–90 μm thick. As the catalytic activity of material of such a coating depends upon the content of the anatase phase in it, further efforts are aimed at finding the way of controlling the phase composition of the TiO_2 coatings produced by plasma spraying of the TiO_2 suspension, as well as at evaluation of the effect of the phase composition of the coatings on their catalytic activity or efficiency of using them for solar cells.

1. Frolov, V.A., Poklad, V.A., Ryabenko, B.V. et al. (2009) Spraying of coatings by feeding aqueous solutions of different compounds into the plasma jet. *Svarochn. Proizvodstvo*, **9**, 47–50.
2. Fauchais, P., Etchart-Salas, R., Rat, V. et al. (2008) Parameters controlling liquid spraying solutions, solids or suspensions. *J. Thermal Spray Technology*, 17(**1**), 31–59.
3. Toma, F.-L., Berger, L.V., Jackuet, D. et al. (2009) Comparative study on the photocatalytic behavior of titanium oxide thermal sprayed coatings from powders and suspensions. *Coating Technology*, **203**, 2150–2156.
4. Toma, F.-L., Bertrand, G., Begin, S. et al. (2006) Microstructure and environment functionalities of TiO_2-supported photocatalysts obtained by suspension plasma spraying. *Appl. Catal. B*, **68**, 74–84.
5. Vassen, R., Yi, Z., Kassner, H. et al. (2009) Suspension plasma spraying of TiO_2 for the manufacture of photovoltaic cells. *J. Surface and Coating Technology*, **203**, 2146–2149.
6. (1969) *Physical-chemical properties of oxides*: Refer. Book. Moscow: Metallurgiya.

INTERNATIONAL EXHIBITION «WELDEX/ROSSVARKA-2010»

The 10th Jubilee International Exhibition «Weldex/Rossvarka-2010» was held from 12 to 15 October in Moscow at EC «Sokolniki». The Exhibition was arranged by Closed Joint Stock Company «International Exhibition Company» and Company «Elsvar» with an assistance of the Ministry of Industry and Commerce of the Russian Federation, Government of the Moscow Region, Moscow Inter-Industry Association of Chief Welders, and Russian Scientific-and-Technical Welding Society.

The welcome addresses to numerous guests and participants at the ceremony of opening of the Exhibition were made by V.I. Lavrukhin, Head of the Department of the Moscow Chamber of Industry and Commerce; A.N. Krutov, Moscow City Duma Deputy; V.A. Kazakov, First Vice-President of the Russian Scientific-and-Technical Welding Society, Director of the «Tekhnologiya Mashinostroeniya» (Machine Building Technology) Publishing House, and Editor-in-Chief of the «Svarochnoe Proizvodstvo» (Welding Production) Journal; O.I. Steklov, President of the Russian Scientific-and-Technical Welding Society; V.N. Butov, President of the Moscow Inter-Industry Association of Chief Welders; and Yu.K. Podkopaev, Director General of the «Elsvar» Company.

«Rossvarka» is the central specialised exhibition of Russia. Therefore, despite the crisis processes in the economy, it reflects the main trends in the welding industry: active search for and advancement of new technologies and equipment providing the high efficiency and competitiveness of production, and technological and environmental safety of structures. Traditionally, the key mission of the Exhibition is to render the maximum possible assistance in promotion of new technologies, materials and advanced developments in the economic space of Russia.

183 enterprises from Russia, as well as from 15 former Soviet Union and foreign countries (Germany, Finland, Sweden, Italy, Ukraine, China, USA, Austria, Turkey, France, Mexico, etc.) took part in the jubilee Exhibition. Exposition of Russian enterprises was most representative at the Exhibition (143 booths). Among them were such famous manufacturers of welding equipment as Closed Joint Stock Company «ITS» (St.-Petersburg), State Ryazan Instrument Plant (Ryazan), Production-Commercial Enter-

prise «Plazer» (Rostov-on-Don), Closed Joint Stock Company «PKTBA» (Penza), Factory for Special Equipment «Tekhnotron» (Cheboksary), Limited Liability Company «Avtogenmash» (Tver), Open Joint Stock Company «Progress NITI» (Izhevsk), as well as manufacturers of welding consumables — Limited Liability Company «Severstal-Metiz» (Oryol), Limited Liability Company «Mezhgosmetiz» (Mstensk), Closed Joint Stock Company «Factory for Welding Consumables» (Berezovsky), Open Joint Stock Company «Losinoostrovsky Electrode Factory» (Moscow), and Limited Liability Company «Sudislavsky Factory for Welding Consumables» (Chelyabinsk).

Ukraine at the Exhibition was represented by the booth of the E.O. Paton Electric Welding Institute, Kramatorsk Enterprise «Donmet», Limited Liability Company «Arksel» (Donetsk), Limited Liability Company «Navkotekh» (Kiev), and journals «Avtomaticheskaya Svarka» (Automatic Welding), «Svarshchik» (Welder) and «Oborudovanie i Instrument dlya Frofessionalov» (Equipment and Tools for Professionals).

The leading companies brands well-known in the world of welding were represented by their divisions in Russia — Limited Liability Company «ESAB» (Sweden), Limited Liability Company «Sabaros» (Switzerland), Limited Liability Company «Kemppi» (Finland), Enterprise «Polysoude S.A.S.» and Limited Liability Company «Air Liquide Welding» (Switzerland), «The Lincoln Electric Company» (USA), Joint Stock Company «IGM Robotersysteme AG», Limited Liability Company «Buehler Welding», «Global Welding Technology» (Austria), GmbH Lorch Schweisstechnik, GmbH Deloro Stellite (Germany), S.P.A. «Sebora» and «MIPA ITALY» (Italy).

Also, a number of leading research, engineering-technologic and engineering centres of Russia, such as the Alliance of Welders of St.-Petersburg and North-West Region (St.-Petersburg), NITI «Progress» (Izhevsk), Open Joint Stock Company» Engineering and Technological Centre «Prometey» (Chekhov), and Moscow Inter-Industry Association of Chief Welders, demonstrated their expositions at the Exhibition.

Welding equipment for different methods of electric arc welding of metals constituted, as a rule, the main volume of the exhibits. The previous trends still persist in development of inverter circuits with microprocessor program synergic control, providing such functions as the hot start, antistick, arc force, substantial saving of power, lower requirements to the skill of welders in ensuring the required welding quality, and insensitivity to mains voltage fluctuations (which is particularly important for welding in building).

Transition in equipment circuits to the totally digital inverter pulse technology provides reproducibility of the welding results with practically absolute absence of molten metal spatters.

In general, the exhibits demonstrated at the Exhibition were in line with the state-of-the-art in welding equipment and equipment for thermal cutting methods (gas, plasma, etc.), and attracted high interest among the specialists who visited the Exhibition.

The majority of specialised exhibitions held in Moscow, St.-Petersburg and Kiev are characterised by the fact that the prevailing quantity of booths demonstrate activities and ranges of goods and services represented by the trading companies. Among them were «Company Avan, Ltd.», «Weber Comechanics, Ltd.», Limited Liability Company «Aleks» (Moscow), Limited Liability Company «Trading House «Argos» (Nizhny Novgorod), Industrial Group «Dyukon» (St.-Petersburg) and many others.

The Scientific and Practical Conference «Innovations in the World of Welding» took place within the framework of the Exhibition. The Conference was dedicated to the 80th anniversary of the «Svarochnoe Proizvodstvo» Journal. The Conference was attended by the leading specialists from a number of major enterprises — members of the Federal Agency on Atomic Energy, structures of Gazprom and Transneft, enterprises of the military-industrial complex, aircraft and space engineering, universities, etc. The focus of the Conference was on the topical problems of improvement and development of welding consumables, equipment for arc and electron beam welding, certification and training of staff.

Traditionally, the Exhibition included competitions «Best Welder of Russia-2010» and «Best Welding Engineer (Scientist) of Russia-2010». The competitions were held in three nominations: manual arc welding, TIG welding, and semiautomatic MIG/MAG welding. In all cases it was necessary to weld the most difficult welds for the above welding processes — position butt welds on pipes with a diameter of 149 mm and wall thickness of 4.5 mm.

During the competitions, all participants and audience could get acquainted with the latest products of leading welding equipment manufacturers, asses their advantages and technological capabilities. But the most important point in the competitions was the skill of the welders admired by the audience.

28 enterprises from Khabarovsk, Moscow, Obninsk, Khimki, Zelenograd, Voronezh, Podolsk, Vladimir, Ivanovo, Novosibirsk and Tyumen took part in the competitions.

P.V. Fetisov (Moscow State Unitary Enterprise «Mosvodokanal») became a winner in nomination «Manual Covered-Electrode Arc Welding». The first place in nomination «TIG welding» was taken by D.N. Balelov (Open Joint Stock Company «Vladimir Production Association «Tochmash»). A.V. Bursevich (Closed Joint Stock Company «Mosflowline») became a winner in nomination «Mechanised Gas-Shielded Welding». The winner in nomination «Best Welding Engineer (Scientist)» was A.V. Shcherbakov, a leading engineer of the Metals Technology Chair of the Moscow Energy Institute, for the development of «Control System for Precision Electron Beam Welding Process». The winners received the excellent prizes — welding devices provided by ESAB (Sweden) and Kemppi (Finland), as well as Russian Company «INSVARKOM-SVAROG» (St.-Petersburg).

Also very impressive was the «Miss Welding of Russia-2010» contest. The girls competed in quality of manual artistic plasma cutting and argon-arc welding, participated in quiz on the history of welding, defiled in special clothes and demonstrated products of the Exhibition participants, recited poetry and sang songs. The winner was Regina Nuritdinova, staff member of the «Orient-Pro» Company and, at the same time, student of the Russian State Technological University «MATI». The handwork crown for the «Miss Welding of Russia-2010» made from steel by a blacksmith-artist from the artistic association of the Factory of Pieces of Art «OST» by using forging and welding

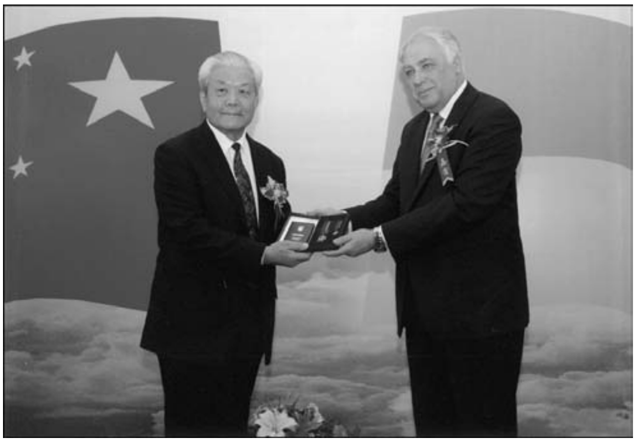
can be considered by right a true work of art. The winner was also awarded a valuable prize — home theatre, which was provided by the «Elsvar» Company, a sponsor of the contest. Gifts to all participants of the contest were presented by the «Donmet» Company (all the girls were presented with copper roses made very skillfully by welding), Factory «Elektrostal», ESAB and Kemppi.

The Exhibition was visited by over 4000 specialists, among which were officials, managers, chief welders and experts of enterprises from different industries, heads and managers of trade companies and trade offices from all regions of Russia and CIS, as well as mass media representatives.

The Scientific and Practical Conference «Innovations in the World of Welding» dedicated to the 80th anniversary of the «Svarochnoe Proizvodstvo» Journal was held during the Exhibition. The Conference was opened by Dr. V.A. Kazakov, Editor-in-Chief of the Journal. He gave a brief retrospective review of development of the Journal, its milestones during 80 years of its existence, and its enormous contribution to improvement of the welding production in the USSR, and then in Russia. Presentations at the Conference were made by Dr. O.I. Steklov, President of the Russian Scientific-and-Technical Welding Society, Dr. V.A. Frolov, Head of the Welding Chair at MATI, Dr. Z.A. Sidlin, Deputy Director of the Limited Liability Company «Tekhprom», A. Zabirov, representative of the Welding Institute in Aachen (Germany), etc.

Prof. V.N. Lipodaev,
Dr. A.T. Zelnichenko, PWI

DECORATION OF CHINESE SCIENTIST



In November 10, 2010 at the Beijing Aeronautical Manufacturing Technology Research Institute (AMTRI) the solemn ceremony was held for decoration of Prof. Guan Qiao, the scientist of Academy of Engineering Sciences of China, with the order of Ukraine «For Merits» of the III degree. The order was presented to the scientist by Yu.V. Kostenko, the ambassador of Ukraine in China (Photo). In the ceremony of presentation Prof. Gao Jian She, vice-president of AVIC, Prof. Li Xiaohong , president of Academy of Fundamental Engineering AVIC, Prof. Zhang Jun, director of the Beijing AMTRI, took part.

During his address to the audience Prof. Guan Qiao outlined:

«First of all let me express my profound appreciation to the Ukrainian government and people of Ukraine for awarding the order «For Merits» of the III degree.

This is a great honor not only for me but also for our Institute. We accepted this order as a symbol of friendship and cooperation between two nations!

At the moment I can't but remind of the history of my relationships with representatives of Ukrainian science, growth of sympathy to Ukraine.

I am engineer-welder, since the 1950s of the last century almost ten years I studied at the N.E. Bauman Moscow STU, where I graduated from the post-graduated courses, then came back home and started working in the Beijing AMTRI.

Already being a student I was astonished at brilliant achievements of welding science and technology in the Soviet Union, especially a great contribution of scientists and specialists of the E.O. Paton Electric Welding Institute to the final victory in the Great Patriotic War.

Also I read with enthusiasm the selected works of E.O. Paton «Welded Structures», which predetermined my choice.

For the last 30 years, having the information about activity of the PWI and extensive relations with the scientists of the PWI, I did my best to familiarize the Chinese colleagues with numerous technologies, latest methods, initiatives and inventions developed at the PWI under the leadership of the Prof. B.E. Paton. They include the processes of electron beam welding, electron beam evaporation to create heat-resistant coatings on gas-turbine blades, non-destructive methods of testing of quality and measuring of stresses in welded structures and their diagnostics, etc. As a result of bilateral cooperation the exchange of specialists between the PWI and Chinese organizations including the Beijing AMTRI was established.

Recently the delegation from the Beijing AMTRI returned from the PWI after summing up of works on the joint project.

Among the specialists of the PWI a number of scientists, in particular Leonid M. Lobanov, Arkady A. Ignatushenko and other visit us regularly in the scope of scientific technical exchange.

I am pleased that this cooperation on actual trends continues to give fruitful results for the welfare of both sides.

During International Conference in 1998 in Kiev devoted to the 80th anniversary of Prof. B.E. Paton I presented the paper at the plenary session in honor of jubilee person and his respect.

The E.O. Paton Electric Welding Institute and Prof. B.E. Paton are recognized widely not only in China, but throughout the world as well. This is a real scientific potential and treasure of Ukraine at the world arena.

I sincerely wish a great prosperity to the Ukrainian science and technology, every happiness to the Ukrainian people!»

K.A. YUSHCHENKO IS 75

Konstantin A. Yushchenko, famous scientist in the field of welding technology and welding materials science, Doctor of Technical Sciences, Academician of the National Academy of Sciences of Ukraine, Professor, Honoured Worker of Science and Technology of Ukraine, laureate of the State Prize of the USSR, Prize of the Cabinet of Ministers of the USSR and Evgeny Paton Prize, and Deputy Director on scientific work of the E.O. Paton Electric Welding Institute, was 75 in December this year.

After graduating from the Kiev Polytechnic Institute in 1958, K.A. Yushchenko started his labour activity at the E.O. Paton Electric Welding Institute, where he worked his way up from engineer-experimentalist to deputy director.

Here he defended his candidate (1965) and doctor (1982) theses, and was awarded the title of professor (1987). He was elected Corresponding Member (1990) and Academician (2003) of the NAS of Ukraine. He was the head of a laboratory (from 1970), and then (since 1978) the head of the Department for Metallurgy and Technology of Welding High-Alloy Steels and Alloys.

The main area of his activities is development of new metallic materials, processes for their production and technologies for welding and surface engineering. The range of research includes development of well-weldable steels and alloys, elaboration of theoretical principles for welding these materials to manufacture parts intended, in particular, for operation under extreme conditions, under the effect of aggressive environments, cryogenic and high temperatures, radiation and intensive magnetic fields.

During a period from 1962 till 1965 K.A. Yushchenko completed a cycle of work on the theory of welding of steels of the ferritic-austenitic grade. He established the principles of variations in physical-mechanical and corrosion properties of metal of a welded joint with multi-component phase composition, and studied the selective character of electrochemical dissolution of phases depending on alloying and linear sizes. This served as a basis for the development of new ingenious systems of steels and welds sparsely alloyed with nickel, welding consumables and processes providing their wide application in chemical engineering. From 1965 K.A. Yushchenko was in charge of the research at the Academy of Sciences of the UkrSSR in the field of development of new weldable steels and alloys for cryogenic engineering. The integrated efforts were made in close collaboration with VNIIKriogenmash, I.P. Bardin TsNIIChermet (Moscow), Chelyabinsk Metallurgical Works (Chelyabinsk), Uralkhimmash (Sverdlovsk), Spetstekhmontazh (Baikonur), factories «Dneprospetsstal», Novo-Kramatorsk Machine-Building Works, Izhora Heavy Machine Building Plant and other organisations of the former Soviet Union. The problem of optimisation of compositions of steel and weld metal was solved on the basis of requirements for high specific strength, resistance to embrittlement under different loading conditions within a temperature range of 4.2–293 K, including in intensive magnetic fields and under irradiation and thermal shock loading. The investigations completed, along with the theoretical work, allowed the development of a range of fundamentally new well-weldable steels for cryogenic engineering, welding consumables and joining processes. For the first time in the world practice the process of melting of cold-resistant steels with the super-low carbon content in 100 t arc furnaces at the Chelyabinsk Metallurgical Works was developed in the USSR. This was used as a basis for the development of a new scientific direction — welding cryogenic materials science, which is recognised not only in the CIS countries, but also abroad. The package of research was completed on evaluation of structural strength of welded joints at cryogenic temperatures. Theoretical investigations were used as a ground for the development of the design codes and methods, which are applied in Ukraine, Russia and other countries to design the new types of cryogenic structures, where low-temperature strengthening of metal is used. More than 50 patented grades of steels, welding wires, electrodes and fluxes developed under the leadership and with participation of K.A. Yushchenko are employed in cryogenic engineering. They were applied in such major projects as «Buran» (launching system), «Tokamak-7» and «Tokamak-15» (superconducting power system of MHD generator), in large-size space simulator, life support unit, onboard engines of space systems, and new generation of gas turbine engines. New steels and consumables, as well as technological processes developed by

K.A. Yushchenko are included as candidates for building of the international fusion reactor «ITER» and stellarator.

In 1985 K.A. Yushchenko developed new postulates concerning the processes that cause cracks in the welds during solidification and reheating. The role of dislocation and segregation processes for the upper and lower brittle temperature ranges, and their part in formation of cracks were theoretically substantiated and experimentally proved. In 1975–2005 K.A. Yushchenko completed the package of work on investigation of weldability of materials. A new theory of weldability was developed, and materials joining methods were classified as to the aggregate state of the matter. The new weldability criterion used to evaluate the degree of degradation of a material from the energy standpoint widens technical capabilities for production of permanent joints in all structural metals and non-metals. Based on investigations of the processes of embrittlement of high-chromium steels of the Fe–20Cr system, having the bcc structure, the team of scientists of the E.O. Paton Electric Welding Institute headed by K.A. Yushchenko, in collaboration with the Physico-Technological Institute of Metals and Alloys of the NAS of Ukraine, suggested to control the segregation phenomena in recrystallisation of metal due to controlled dispersion of impurities in the bulk of grain. This work opened up a new advanced direction in development of mass-application well-weldable nickel-free corrosion-resistant high-chromium ferritic steels.

One of the scientific achievements is the theory of welding of high-alloy steels with super-equilibrium nitrogen content, which was developed by K.A. Yushchenko and co-workers. The cycle of the work allowed substantiating the principles of providing sound joints on a new grade of metals characterised by super-equilibrium alloying with gases. Investigations on the kinetics of denitriding made it possible to determine the conditions of existence of quasi-equilibrium states in interface regions of solidifying metal, as well as the role of phase changes of metal in the «liquid–gas» system. Consumables and processes allowing welding of metal with a super-equilibrium nitrogen content of up to 1 % were developed for the first time in the world practice.

In 1986–2005 K.A. Yushchenko took an active part in the work on the development of new consumables and processes for treatment of surfaces and deposition of coatings. He conducted investigations on the development and application of special flux-cored wires for wear- and corrosion-resistant surfacing, new types of wires and powders based on refractory materials, and compositions of alloys with amorphous structure. The consumables and processes developed found wide commercial application. They include such processes as vanadium carbide plating, plasma-detonation treatment, discharge-plasma treatment and microplasma spraying. Being original, many of them were covered by patents and found recognition abroad.

K.A. Yushchenko is very active in organisation of science. In 1989 he was elected a Vice-President of the International Institute of Welding. From 1986 till 1992 he was a Vice-Chairman of the National Welding Committee of the USSR, since 1993 — Chairman of the National Welding Committee of Ukraine, and since 1990 — leader of area «Permanent Joints and Coatings» and program «New Substances and Materials». He is the Head of the Coating Section at the CIS Inter-State Science and Technology Council, and since 1983 — member of Bureau of the Department for Physical-Technical Problems of Materials Science at the NAS of Ukraine, member of the Specialised Board on Defence of Theses at the E.O. Paton Electric Welding Institute, member of editorial boards of the «Avtomaticheskaya Svarka» (Automatic Welding) and «Svarshchik» (Welder) journals, member of the Technical Committee and Select Committee on joining and coating of advanced materials for aircraft engineering at the International Institute of Welding. Since 1984 he is a member of management boards of the international organisations on cryogenic engineering and cryogenic materials.

K.A. Yushchenko is the author of more than 750 publications and inventions, including 7 books. Over 40 candidate and 6 doctor theses were trained under his supervision.

K.A. Yushchenko was awarded the Honorary Diploma of the Supreme Soviet of the UkrSSR, Order of Friendship of People, Order of Yaroslav the Wise of the V degree, and medals. In 1994 he was elected an active member of the International Electrotechnical Academy (Moscow).

Associates of the E.O. Paton Electric Welding Institute and Editorial Board of «The Paton Welding Journal» sincerely congratulate Konstantin A. Yushchenko with his glorious jubilee and wish him strong health, happiness and new creative achievements.

INDEX OF ARTICLES FOR TPWJ'2010, Nos. 1–12

INFORMATION

NEWS

SCIENTIFIC AND TECHNICAL

SERVICE LIFE OF WELDED STRUCTURES

LIST OF AUTHORS

SUBSCRIPTION
FOR «THE PATON WELDING JOURNAL»

If You are interested in making subscription directly via Editorial Board, fill, please, the coupon and send application by fax or e-mail.

The cost of annual subscription via Editorial Board is $324.

Telephones and faxes of Editorial Board of «The Paton Welding Journal»:

Tel.: (38044) 200 82 77, 200 81 45

Fax: (38044) 200 82 77, 200 81 45.

«The Paton Welding Journal» can be also subscribed worldwide from catalogues of subscription agency EBSO.

SUBSCRIPTION COUPON

Address for journal delivery ____________________

____

Term of subscription since ________ **20** ____ **till** ________ **20** ____

Name, initials ____________________

Affiliation ____________________

Position ____________________

Tel., Fax, E-mail

ADVERTISEMENT
IN «THE PATON WELDING JOURNAL»

External cover, fully-colored:

First page of cover (190×190 mm) – $700

Second page of cover (200×290 mm) – $550

Third page of cover (200×290 mm) – $500

Fourth page of cover (200×290 mm) – $600

Internal cover, fully-colored:

First page of cover (200×290 mm) – $350

Second page of cover (200×290 mm) – $350

Third page of cover (200×290 mm) – $350

Fourth page of cover (200×290 mm) – $350

Internal insert:

Fully-colored (200×290 mm) – $300

Fully-colored (double page A3) (400×290 mm) – $500

Fully-colored (200×145 mm) – $150

Black-and-white (170×250 mm) – $80

Black-and-white (170×125 mm) – $50

Black-and-white (80×80 mm) – $15

- Article in the form of advertising is 50 % of the cost of advertising area
- When the sum of advertising contracts exceeds $1000, a flexible system of discounts is envisaged

Technical requirement for the advertising materials:

- Size of journal after cutting is 200×290 mm
- In advertising layouts, the texts, logotypes and other elements should be located 5 mm from the module edge to prevent the loss of a part of information

All files in format IBM PC:

- Corell Draw, version up to 10.0
- Adobe Photoshop, version up to 7.0
- Quark, version up to 5.0
- Representations in format TIFF, color model CMYK, resolution 300 dpi
- Files should be added with a printed copy (makeups in WORD for are not accepted)