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METHODOLOGY FOR CONTROL OF FITNESS FOR PURPOSE OF FLASH BUTT WELDED JOINTS IN PIPELINES

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Requirements to circumferential welded joints in large-diameter pipelines are considered. Results of experimental studies of strength and deformability of flash butt welded joints on standard and large-scale specimens are generalised. It is shown that development of a test procedure and requirements for toughness of the weld metal, allowing for specific peculiarities of formation of the flash butt welded joints, is required to control fitness for purpose of the joints.

K e y w o r d s : flash butt welding, pipeline, welded joint, defects, performance, test criteria, large-scale specimens, requirements to properties, fitness for purpose

Increasing upgrading of technology for construction of main pipelines, application of new grades of pipe steels and utilisation of advanced diagnostics and test means make it necessary to fundamentally revise technical specifications that identify requirements to welded joints. This is especially true for evaluation of the quality of circumferential welded joints made under field conditions [1]. Methodology for estimation of fitness for purpose of the joints made by different arc welding methods is described in detail in studies [2, 3]. It was developed with allowance for technological peculiarities of welding and conditions of subsequent operation of metal structures. Along with electric arc welding, automatic flash butt welding (FBW) is also applied to advantage for construction of pipelines. Utilisation of this welding method holds high promise for construction of new pipeline systems. The joints made by FBW greatly differ from those made by the electric arc welding methods both in metal structure and in shape (Figure 1). Therefore, identification of the main criteria to specify requirements for properties of the FBW joints is very important for development of corresponding regulatory documents.

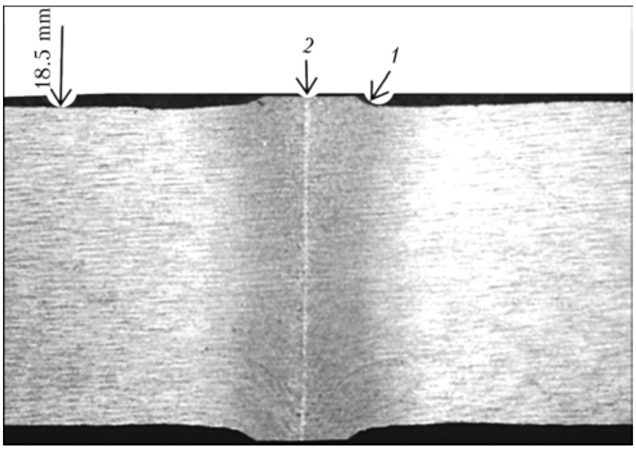

Figure 1. Macrosection of FBW joint: *1* — location of stress concentration caused by shape of the joint; *2* — JZ

This study is dedicated to analysis of requirements imposed on welded joints made by electric arc welding methods, as well as to development, on this basis, of principles and initial provisions on methodology for control of fitness for purpose of the FBW joints, allowing for specific features of this welding method in terms of the weld formation. The study also considers requirements to characteristics of welded joints which are monitored during the pipeline construction process, to secure their load-carrying capacity. Of high importance among them are the following characteristics: mechanical properties of metal of the joints provided on specimens with a reinforcement removed flush with the base metal, such as strength (tensile strength σ_t of the weakest region) and deformability (bend angle α); geometric parameters of shape of a welded joint, which determine stress concentration level α_σ within the joining zone (JZ); difference in properties of metal of the joint (hardness HV); energy consumed for fracture of standard specimens of welded joints (impact toughness KCU or KCV); and admissibility and size of the most probable defects detected by visual examination and non-destructive testing methods.

In arc welding, such defects include undercuts, lacks of penetration, pores, non-metallic inclusions (slags), and edge displacement. According to specifications, welded joints with the above defects are considered fit for service provided that their sizes are not in excess of the permitted ones. In addition to the above defects, the arc welding methods are also characterised by such dangerous damages as cracks, which result from chemical and physical heterogeneity formed in the weld metal. Formation of the former is related to a different degree of solubility of chemical elements, depending upon the state of metal (solid or liquid) and diffusion processes occurring at an increased cooling rate, whereas the latter is caused by formation of secondary boundaries passing through the regions where imperfections of crystalline lattices are concentrated [4].

Welded joints containing cracks, independently of location of the latter, their size and orientation, are not permitted for operation. At the same time, even a 100 % NDT cannot guarantee the absence of cracks, because of its limited resolution and subjective factors. Elimination of fractures in this case can be provided by a sufficient safety factor for toughness of the welded joint metal, which allows the level of stresses within the zones of stress raisers (including cracks) to be decreased without initiation of fracture due to plastic deformation. The required level of metal toughness is specified depending upon the service conditions (working and residual stresses, temperature, etc.), as well as size of the most probable (hypothetical) crack-like defect, using the well-known concept of fitness for purpose based on approaches and criteria of fracture mechanics. The latter correlate with a value of impact toughness *KCV* determined on standard specimens with a sharp notch [5].

It can be well seen from the above-said that the test methods for evaluation of toughness of the welded joint metal and its rated level relate to the types and sizes of defects characteristic of the electric arc welding methods. The challenge now is to do the same for the FBW joints.

FBW is widely and successfully employed in different industries, including construction of main pipelines [6–8]. Increasing interest in this welding method is explained by a combination of high and consistent quality of the joints made by FBW, their cost effectiveness, high productivity of welding operations, and service reliability of the welds. Skipping all benefits of this advanced method for welding circumferential butt joints in main pipelines, we will dwell only on those characteristic features that are associated with the load-carrying capacity of such joints.

The key feature among them is that dozens of thousands of kilometres of different pipelines, including high-capacity main gas pipelines with a diameter of 1420 mm, have been in operation without failure for over 30 years in different regions of CIS, which are characterised by severe natural and climatic conditions (e.g. arctic regions of Western Siberia, and deserts of Turkmenia). This very fact can serve as an indicator of their high strength and endurance. Also, this was proved by investigations conducted by the E.O. Paton Electric Welding Institute. The investigations were carried out on large-scale specimens cut from pipes (along the generating line) of domestic production (Khartsyzsk Pipe Plant) and imported pipes (Companies of Germany, Japan and Italy). The pipes of low-carbon low-alloy steels of strength grades X60–X70 had an outside diameter of 1420 mm and wall thickness of 14.7–20.0 mm. Circumferential joints on them were made under the welding conditions common for construction of pipelines [9]. Segmented specimens from 160 to 500 mm wide, with a flash removed in compliance with the standards (reinforcement of no more than 3 mm) or flush with the base metal, were tested under tension conditions using the tensile testing machines with a load of 3000 and 8000 kN in a wide temperature range (–60 – +20 °C). All specimens of the welded joints made under optimal welding conditions to guarantee their quality fractured in the base metal (BM). The results of testing the standard specimens cut from the sound welded joints with a flash removed flush with BM also confirm that the joints meet requirements of the standards for strength and deformability [10, 11]. Fracture of smooth specimens in tensile tests occurred outside the JZ at a stress of not lower than the rated value of tensile strength of the pipe metal (Figure 2, *a*). The bend angle in each specimen was much in excess of a set arithmetic mean of 70° (Figure 2, *b*). Most specimens were bent to 180° without cracking of the welded joint metal.

It is a known fact that strength of welded joints is greatly affected by stress raisers. Moreover, tensile residual stresses, as well as structural and mechanical heterogeneity of the joint metal, may also have a negative effect at the presence of defects. So, we will consider the FBW joints from this standpoint.

Figure 1 shows geometry of the FBW joint after removal of flash from its both sides. The calculations made on the basis of the results of measuring profile of the joint show that the stress concentration induced by it is consistently low. The mean value of the stress concentration factor is $\alpha_\sigma \leq 1.1$, the variation range being 1.05–1.13. In terms of performance of welded

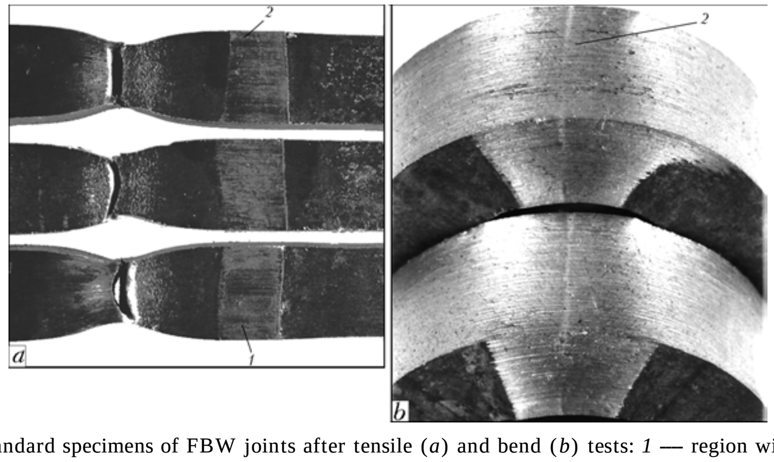

Figure 2. Appearance of standard specimens of FBW joints after tensile (*a*) and bend (*b*) tests: *1* — region with removed flash; *2* — JZ

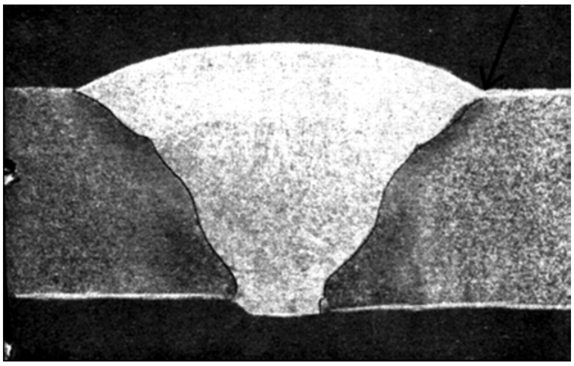

Figure 3. Macrosection of circumferential welded joint produced by manual electric arc welding: location of a stress raiser coinciding with JZ is indicated by an arrow

Figure 4. Distribution of microhardness HV in metal of a welded joint depending upon distance l from JZ

joints, an important point is the offset of location of a stress raiser and JZ, which is the case, e.g. of electric arc welding methods (Figure 3). In the last case the fusion zone is termed in literature the «local brittle zone», because of a decreased fracture initiation resistance. For butt welded joints containing this zone, made by two-sided submerged-arc welding on pipe steels of controlled rolling, it was necessary to develop the methodology for estimation of their fit for purpose and identify requirements for their fracture toughness [12]. In this connection, JZ in FBW also receives special emphasis. As indicated by the results of investigation of the JZ metal in sound joints, it has a lower carbon content than the pipe metal [13, 14], and a lower hardness than the adjoining regions of the thermomechanically affected zone (TMAZ) [7, 15], which causes some increase in ductility of the JZ metal (Figure 4). Moreover, JZ contains no micro and macro defects, and it shares grains with the base metal of pipes. All this is indicative of the fact that JZ cannot be the zone of initiation of fracture of a welded joint. In the case of a forced initiation of fracture in JZ, when testing standard specimens with an artificial stress raiser, cracks most often propagate into a more brittle TMAZ, where the fracture resistance is lower than in JZ. As shown by fractography, when fracture occurs in JZ, the fracture surface comprises micro regions looking like a tough fracture (Figure 5, *a*), whereas appearance of the fracture surface in TMAZ is typical of a brittle fracture (Figure 5, *b*).

However, TMAZ, like JZ, is not a zone of initiation of fracture, as no cracks or other defects characteristic of the arc welding methods are formed in it. This is attributable to peculiarities of formation of a welded joint containing no cast metal.

The test results show that the joints made by FBW under optimal conditions are practically defect-free. In addition, owing to the simultaneous formation of a joint on the entire perimeter of a pipe, residual stresses formed in JZ are insignificant.

At this point it is important to consider the system of assurance of a high and consistent quality of the FBW joints. First of all, this is the up-to-date level of this welding method and equipment used for its implementation, which is based on the latest R&D achievements. The method involves no welding consumables, which is an important factor that strongly affects properties of a joint. The process of welding a butt joint, which lasts for 60–180 s, is performed in the automatic mode following the preset program without any intervention by a welding operator, which excludes the effect of a subjective factor on the quality of the joint. Meeting all requirements for ensuring a sound joint at the preparatory stage is followed by the final stage — formation of a welded joint on the entire section of the weld edges. The computerised system fixes all main process parameters (current, voltage, time and distance of movement of the mobile part of the welding machine, used to calculate the

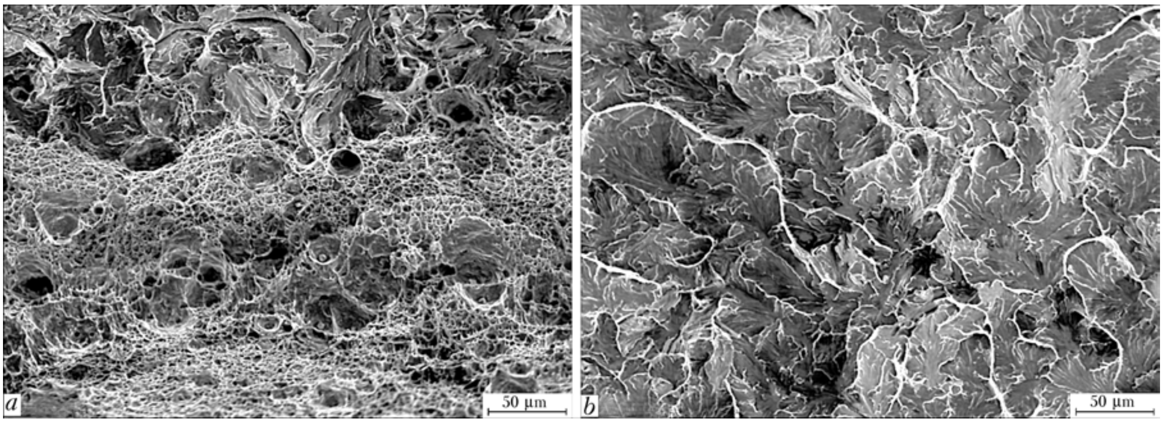

Figure 5. Fractograms of fracture surfaces in propagation of crack in JZ (*a*) and TMAZ (*b*)

speed of flashing, forcing and upsetting) for each joint during the entire welding process. Optimal conditions for formation of reliable welded joints were established on the basis of analysis of their variations, compared with quality of the resulting joints. Deviation of any parameter from a set value during the welding process is fixed by the welding parameters monitoring system. The derived information is processed, and after that a command is fed to stop welding, if the deviation occurred at the preparatory stage of the process, or to reject a joint, if the deviation took place at the joint formation stage.

As shown by examinations of the joints made under field conditions and a long-time service experience, correspondence of the welding process parameters to specification values guarantees the required quality of welded joints and their high serviceability. Such joints may have only local concentrations of non-metallic inclusions in some JZ regions, having a maximal area of 20–30 mm^2 (in a number of studies such regions are called the grey spots (GS) [15]. They can be visually examined on the fracture surface, as they stand out against the background of a crystalline fracture (Figure 6). Grey spots are characterised by microstructural heterogeneity. The regions of fractured metal in JZ and uniformly distributed non-metallic inclusions, located over the entire GS area, can be well detected in magnification. Non-metallic inclusions are segregation inclusions or fine (less that 50 μm) oxide films, which are fragmented during upsetting. Structures of these two types of non-metallic inclusions on fracture surfaces are almost identical. The causes and mechanism of their formation are studied in detail in [16, 17].

Large-scale specimens were tested to evaluate the effect of non-metallic inclusions on performance of welded joints at a temperature of –60 – +20 °C. One series of specimens had low residual stresses (σ_{res} = = $(0.2–0.3)\sigma_{0.2}$), which usually take place in FBW of pipes, and in the second series of specimens the values of σ_{res} were close to $\sigma_{0.2}$. These residual stresses were induced in specimens by depositing longitudinal beads (on two sides) with a spacing of about 50–60 mm within the zone of a transverse joint. The investigations show that GS, even of a large area (totally, up to 30–40 % of the fracture surface), deliberately induced in JZ by a certain deviation of the welding process parameters from the rated values, have no effect on static strength of the joints. Therefore, grey spots are considered to be a structural heterogeneity of the JZ metal, rather than defects.

Inadmissible deviations of some welding process parameters may lead to formation in JZ of lacks of fusion, having the form of unclosed craters (UC) or fragmented oxide films (FOF), up to 100 μm thick. UC are small discontinuity regions up to 5 mm in diameter, which are formed in JZ at an insufficient upsetting allowance. Their effect on performance of welded joints was considered in study [18].

Under the conditions that favour interaction of metal heated to a temperature close to the melting point with air oxygen, even with optimal upsetting, some FOF are formed in JZ, which in composition are almost identical to non-metallic inclusions in GS, but have not only a larger thickness, but also a larger area. Such fragments of FOF can be seen on the fracture surfaces with an unaided eye. Metallic bond is formed in regions of disruption of the films between the weld edges (i.e. FOF is a defect with partial welding). This bond is caused by the fact that FOF have a considerable content of lower oxides of the MeO type (FeO, MnO), with crystalline lattices identical in structure and size to those of α-iron [17].

The effect of the above defects on strength of pipe welded joints was evaluated by the results of testing several batches of large-scale specimens of the same size as the sound joints under consideration. The only difference was that they were welded under special optimised conditions with deliberate gross violations of the technology to form defects of the above types in JZ. The sensitivity of welded joints to this or other defects was estimated from the ratio of rated fracture stresses to a rated value of yield stress $\sigma_{0.2}$ of BM. The results of these studies within a range of natural climatic temperatures, including –60 °C, are shown in Figure 7.

The presence of FOF at low temperatures leads to a certain decrease in fracture resistance of the defective weld regions. Thus, at –60 °C the critical value of the total FOF area in the weld, estimated from a condition that $\sigma_f = \sigma_{0.2}$ (here σ_f is the fracture stress), is approximately 180 mm^2 (solid curve *1* in Figure 7).

As shown by the results of testing the specimens at temperatures of –60 and –40 °C with a weld edge displacement, the permissible value of edge displacement is up to 25 % of the pipe wall thickness [18]. A combination of edge displacement and FOF enhances their effect. At –60 °C and maximum permissible edge displacement (25 %), the total critical value of the FOF area decreases to 70 mm^2 (solid curve *2* in Figure 7). Increase in temperature leads to increase in the total FOF area in welded joints both with and without edge displacement (see dash-dotted curves *1* and *2*, respectively, in Figure 7). Defects of the FOF type, combined with edge displacement, are identical to UC in the degree of their effect on strength of the welded joints (see solid curves *2* and *3*, respectively, in Figure 7).

Of fundamental importance for assuring serviceability of welded joints is that inadmissible defects of

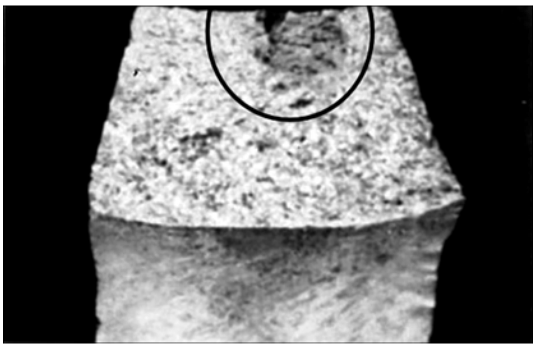

Figure 6. Grey spots on fracture surface (delineated region)

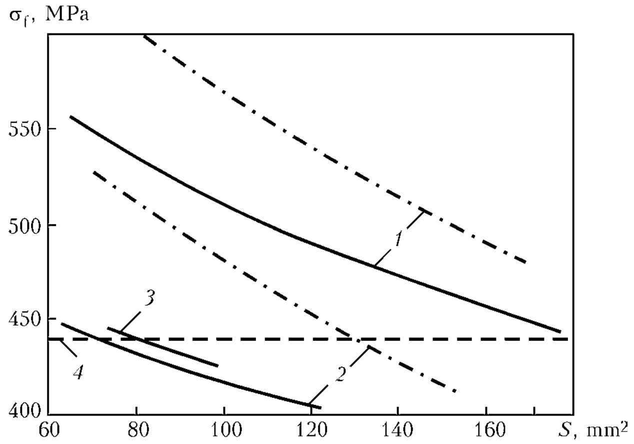

Figure 7. Level of fracture stresses σ_f in large-scale specimens of FBW joints depending upon total area *S* of defects in JZ: *1* — FOF; *2* — FOF combined with maximum permissible (25 %) edge displacement; *3* — UC; *4* — rated value of yield stress $\sigma_{0.2}$ of pipe metal; solid curves — test temperature of –60 °C; dash-dotted curves — test temperature of +20 °C

the established sizes, typical of the joints made by FBW with violation of the welding process parameters, can be reliably detected by non-destructive test methods. The most efficient among them is ultrasonic inspection [19–21], which makes it possible to detect UC and FOF at a sufficient level of confidence. Along with assuring quality of the weld by maintaining the FBW process parameters within the set limits, this is another extra means for improving the operational reliability of welded joints [22]. In addition, toughness of the weld metal should also be monitored and maintained at a rated level. This point is worthy of separate investigation. It should be noted that the laboratory procedure for testing small standard specimens should be developed with allowance for the characteristic defects of the FBW joints and the concentration of stresses induced by them. The results of testing standard and large-scale specimens of sound joints and joints containing defects, considered in this study, can serve as a basis for specifying requirements for toughness of the weld metal.

CONCLUSIONS

1. Experience in operation of large-diameter main pipelines and results of tests of large-scale specimens showed a high level of performance of FBW joints, which was confirmed by systematic proof tensile and bend tests of standard specimens subjected to static loading.

2. Because of the absence of cast metal in FBW, this welding process does not create conditions for formation of cracks or other defects characteristic of the arc welding methods. In sound welded joints, only the individual regions of JZ had concentrations of non-metallic inclusions with a maximal area of up to 20–30 mm^2. Strong bond of the latter with matrix allows their classification as structural heterogeneity of the JZ metal, which has no effect on performance of welded joints.

3. Quality of the FBW joints is ensured by monitoring and computer system support (for the entire process of welding each joint) of the process parameters at a set level.

4. Inadmissible deviations of welding process parameters from the optimal values may lead to formation of defects in JZ, characteristic of FBW, i.e. UC and FOF. According to the results of testing large-scale specimens within a temperature range of –60 – +20 °C, the critical value of their area is in access of 70 mm^2. Such defects can be reliably detected by ultrasonic inspection.

5. Procedure for evaluation of toughness of metal of the FBW joints, as well as its required level should be assigned with allowance for the characteristic defects (UC and FOF) and their effect on strength.

6. Monitoring and meeting requirements to the welding process parameters, standard mechanical properties (σ_t and α), content of defects and substantiated level of toughness of metal of FBW joints are a guarantee of their high quality under service conditions.

1. *SP 105-34–96*: Guidelines. Welding operations and quality control of welded joints. Introd. 01.10.96.
2. Ivantsov, O.M. (1985) *Reliability of main pipeline welded structures*. Moscow: Mashgiz.
3. Moldavanov, O.I., Orekhov, V.I., Shishov, V.N. (1986) *Industrial inspection in pipeline construction*. Moscow: Nedra.
4. Deev, G.F., Patskevich, I.O. (1984) *Weld defects*. Kiev: Naukova Dumka.
5. Girenko, V.S., Dyadin, V.P. (1985) Relation between impact strength and criteria of fracture mechanics of structural steels and their welded joints. *Avtomatich. Svarka*, **5**, 13–20.
6. Paton, B.E., Lebedev, V.K., Kuchuk-Yatsenko, S.I. (1979) Complex «Sever-1» for flash-butt position welding of large diameter pipes. *Ibid.*, **11**, 41–45.
7. Kuchuk-Yatsenko, S.I. (1986) *Flash-butt welding of pipelines*. Kiev: Naukova Dumka.
8. Mazur, I.I., Serafin, O.M., Karpenko, M.P. (1988) Electric resistance welding: Ways of improvement. *Stroitelstvo Truboprovodov*, **4**, 8–11.
9. *VSN 006–89*: Instructions on technology for flash-butt welding of main pipelines with tensile strength of up to 60 kgf/mm^2. Moscow: VNIIST.
10. *SNiP III-42–80*: Building norms and rules. Rules for performance and acceptance of operations. Main pipelines. Moscow: Gosstroj SSSR.
11. (1988) *API Standard 1104*: Welding of pipelines and related facilities. Washington: API.
12. Kirian, V.I., Semyonov, S.E. (1995) Assessment of fitness for purpose of welded joints in main pipeline of microalloyed steels. *Avtomatich. Svarka*, **3**, 4–9.
13. Gelman, A.S., Kabanov, N.S. (1957) *Flash butt welding of pipes*. Moscow: Mashgiz.
14. Kabanov, N.S., Slepak, E.Sh. (1970) *Technology of flash butt welding*. Moscow: Mashgiz.
15. Kuchuk-Yatsenko, S.I., Lebedev, V.K. (1965) *Continuous flash butt welding*. Kiev: Naukova Dumka.
16. Kuchuk-Yatsenko, S.I., Kazymov, B.I., Zagadarchuk, V.F. et al. (1984) Formation of «grey spots» in joints made by flash butt welding. *Avtomatich. Svarka*, **11**, 23–26.
17. Kuchuk-Yatsenko, S.I. (1992) *Flash butt welding*. Kiev: Naukova Dumka.
18. Trufyakov, V.I., Mazur, V.G., Zhemchuzhnikov, G.V. et al. (1987) Influence of some defects on strength of flash-butt welded joints. *Avtomatich. Svarka*, **2**, 7–9.
19. Troitsky, V.A., Radko, V.P., Yushchak, P.T. et al. (1981) Ultrasonic quality control of joints made by flash butt welding. *Ibid.*, **4**, 38–40.
20. Troitsky, V.A., Radko, V.P., Demidko, V.G. et al. (1986) *Non-destructive testing of welded structure quality*. Kiev: Tekhnika.
21. Radko, V.P., Troitsky, V.A., Kazymov, B.I. et al. (2006) Investigation and specifics of location of oxide film type defects in ultrasonic inspection of joints made by flash butt welding. In: *Proc. of 5th Nat. Sci.-Techn. Conf. and Exhibition on Non-Destructive Testing and Technical Diagnostics* (Kiev, 10–14 April, 2006). Kiev.
22. Kuchuk-Yatsenko, S.I., Kazymov, B.I., Radko, V.P. (1996) Comprehensive inspection of joints made by automatic flash butt welding. *Tekhnich. Diagnostika i Nerazrush. Kontrol*, **4**, 46–50.

INFLUENCE OF OXYGEN POTENTIAL OF WELDING FLUXES ON SOLID SOLUTION ALLOYING IN WELD METAL

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Calculation-experimental procedure was used to predict the ferritic matrix alloying level in a low-alloyed weld metal. Results of comparison of calculations made by the suggested procedure with the experimental data are presented, showing high reliability of the obtained predictions. A conclusion is made on the possibility of using the suggested procedure both for calculation of the solid solution alloying level and for evaluation of the optimal level of the oxidation potential of welding consumables.

K e y w o r d s : arc welding, low-alloyed steels, welding fluxes, weld metal, ferritic matrix, alloying level, oxidizing potential, design-experimental procedure

Metallurgical activity of agglomerated fluxes is determined by their ability, depending on composition, to alloy or oxidize the weld metal, intensify metallurgical reactions in the gas, slag or metal phases. The paper gives the results of computer simulation of the experiments on studying the ability of agglomerated fluxes to alloy the weld metal or bind into oxides and nitrides the alloying or other impurities, which were added by some method to the weld pool.

Solid solution alloying allows essentially by changing both the weld metal structure and their mechanical properties. A lot of attention is traditionally given to this influence. Relationship between ferrite alloying, its structure and mechanical properties is described in studies [1–3], which lead to a conclusion on the urgency of studies in the field of prediction (and, therefore, intelligent control) of the content of alloying elements in the solid solution.

In the studies the process of ferritic matrix alloying is usually considered as a chain of successive reactions. Such an approach is readily illustrated in [4], which gives the schematic (Figure 1), from which it is seen that at weld cooling first oxidation of alloying elements proceeds, then that part of them, which did not react with oxygen, forms nitrides, and the amount of alloying elements, which remained unbound either by oxygen or nitrogen, dissolves in the ferritic matrix. Such a succession of reactions in the weld pool and metal of the cooling weld is formalized to a certain extent, being, however, convenient for calculations.

Computer simulation of the oxidation processes allows determination of the quantity of alloying elements, not bound into oxides [5], which goes into the nitride forming reactions. In this case, calculations related to nitride formation, are based on the results obtained in computer simulation of the alloying element oxidation processes and allowing for the fact that the slag phase, as a rule, is not a source of nitrogen penetration into the weld pool. Welding consumables, having nitrogen-containing components, for instance nitrous ferromanganese or boron nitride in their composition, can be an exception. Such cases are quite rare, and not considered in this study. Nitride formation can be presented in the form of the following reactions [6]:

$$5Mn + N_2 \leftrightarrow Mn_5N_2;\ \Delta G^0_{298} = -201800 + 192.17T, \quad (1)$$

$$3Si + 2N_2 \leftrightarrow Si_3N_4;\ \Delta G^0_{298} = -749440 + 96.3T, \quad (2)$$

$$2Al + N_2 \leftrightarrow 2AlN;\ \Delta G^0_{298} = -320290 + 20.93T, \quad (3)$$

$$2Ti + N_2 \leftrightarrow 2TiN;\ \Delta G^0_{298} = -336620 + 30.31T. \quad (4)$$

Proceeding from measurement results considered in [7], we will assume the weld pool temperature of 2043 K. For this temperature

$$\Delta G^0_1 = 191,\ \Delta G^0_2 = -553,\ \Delta G^0_3 = -277,\ \Delta G^0_4 = -275\ \text{kJ}.$$

It is seen from calculations that the process of manganese nitride formation starts only at temperatures below 1050 K.

Amount of nitrogen consumed in nitride formation can be found from the following expression:

$$\Sigma n_N = 2 / 5n_{Mn} + n_{Ti} + 4 / 3n_{Si} + n_{Al},$$

where Σn_N is the summary amount of nitrogen (g / mol) bound into nitrides; n_{Mn}, n_{Ti}, n_{Si}, n_{Al} is the amount of nitrogen (g / mol) entering into the reaction with manganese, titanium, silicon and aluminium, respectively.

Knowing nitrogen content in weld metal, value of free energy of nitride-forming reactions and using the calculation procedure given for the case of oxidation reactions [5], it is possible to determine the amount of alloying elements reacting with nitrogen.

To check the correspondence between the calculation data and experimental results, experiments were conducted, in which butt joints on low-alloyed steel 20 mm thick were prepared by EN 1597–1 procedure [8], which envisages obtaining specimens of pure deposited metal. Welding was performed using test agglomerated fluxes in combination with Sv-08GA wire of 4 mm diameter.

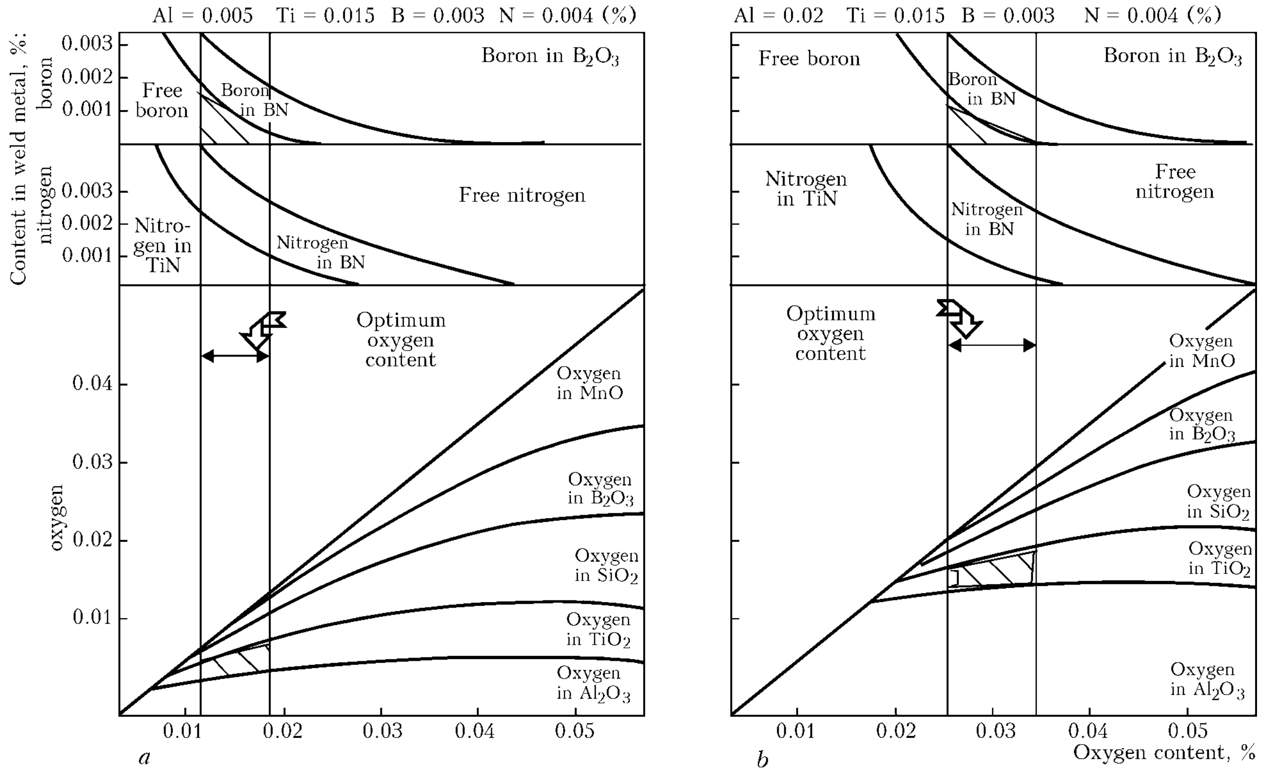

Figure 1. Schematic of calculation of optimum content of oxygen in the low-alloyed weld metal [4] at a low (*a*) and high (*b*) content of aluminium in the metal

Test fluxes were based on $MgO–Al_2O_3–SiO_2–CaF_2$ slag system. Possibility of changing the flux oxygen potential was provided by variation of component proportion. The oxygen potential was determined by measuring the partial pressure of oxygen above slag melt P_o with subsequent calculation by formula $\pi_o = RT \ln (P_o)$. In order to study the influence of various deoxidizer elements on the level of solid solution alloying, aluminium, titanium and silicon were added to the charge composition by a program given in Table 1. Experiments were conducted using fluxes of a higher bacisity (π_o = –369), neutral (–337) and acid type (–307 kJ / mol).

Sections for metallographic analysis were cut out of the metal deposited using test fluxes. During electron microscopy examination weld metal structure, as well as solid solution composition, were studied.

Table 1. Content of deoxidizer elements in test agglomerated fluxes

Experiment No.	Oxygen potential of the flux π_i, kJ / mol	Content of deoxidizer elements in the flux charge, wt.%		
		Al	Ti	Si
1A	–369	0.5	–	–
1T		–	0.4	–
1AT		0.5	0.2	–
2A	–337	0.5	–	–
2S		–	–	0.5
2SS		–	–	1.0
3S	–307	–	–	0.5
3SS		–	–	1.0
3AT		0.5	0.2	–

Calculation results for some weld metal compositions are given in Table 2. Figure 2 gives the results of comparison of calculated content of alloying elements in the solid solution (data of Table 2) and alloying element content in the solid solution obtained at analysis of deposited metal microsections in an electron microscope fitted with X-ray spectral attachment «Link». As is seen from the above data, calculated values of alloying element content in ferrite agree quite well with the results of experiments. Therefore, it is admissible to consider the calculated values as such which with a certain degree of accuracy allow evaluation of the level of solid solution alloying. Additional experiments on quantitative evaluation of the composition of microstructural components of deposited metal samples were performed to verify the made assumption.

Table 3 gives the results of determination of the content of microstructural components in the deposited metal of test welds. Data given in the Table, were compared with the results of calculation of the content of alloying elements in the solid solution.

Analysis of both the calculated and experimental data leads to the following conclusion: while in welding with acid type fluxes (π_o = –307 kJ / mol) the solid solution is alloyed mainly with manganese and silicon, in case of using fluxes of a higher basicity (π_o = –369 kJ / mol), substantial amounts of aluminium and titanium are present in the solid solution. Such differences in ferrite alloying should certainly affect the conditions of its structure formation.

Figures 3–5 give the results of comparison of calculated values of alloying element content in the solid solution with the quantity of certain structural components of weld metal.

Table 2. Results of calculation of the amount of alloying elements entering into the reaction of oxidation and nitride formation

Experiment No.	Fraction of alloying elements (wt.%) contained in							
	weld metal				oxides			
	Mn	Si	Ti	Al	Mn	Si	Ti	Al
1À	0.86	0.24	0.025	0.025	0.405	0.12	0.001	0.01
1Ò	0.70	0.22	0.025	0.019	0.224	0.109	0.012	0.008
1ÀÒ	0.75	0.29	0.01	0.029	0.279	0.153	0.0002	0.011
2A	0.73	0.38	0.01	0.02	0.229	0.291	0.0008	0.001
2S	0.85	0.30	0.013	0.01	0.208	0.234	0.0001	0.009
2SS	0.84	0.26	0.01	0.01	0.164	0.181	0.0071	0.009
3S	0.98	0.45	0.012	0.02	0.236	0.342	0.007	0.01
3SS	0.86	0.40	0.023	0.01	0.144	0.323	0.014	0.0069
3AT	0.88	0.44	0.017	0.02	0.169	0.381	0.0072	0.0134

Table 2 (cont.)

Experiment No.	Fraction of alloying elements (wt.%) contained in							
	nitrides				solid solution			
	Mn	Si	Ti	Al	Mn	Si	Ti	Al
1À	0	0.082	0.022	0.014	0.451	0.048	0.001	0.0001
1Ò	0	0.064	0.013	0.01	0.466	0.027	0.001	0.0002
1ÀÒ	0	0.087	0.005	0.017	0.471	0.026	0.0028	0.0002
2A	0	0.045	0.008	0.01	0.51	0.034	0.0032	0
2S	0	0.025	0.009	0	0.64	0.031	0.0033	0.001
2SS	0	0	0	0	0.68	0.039	0.0039	0.001
3S	0	0	0.002	0.005	0.744	0.078	0.0041	0.002
3SS	0	0	0.005	0	0.746	0.071	0.0049	0.003
3AT	0	0	0.002	0.002	0.751	0.064	0.0092	0.0056

Investigation of the influence of solid solution alloying on weld metal structure was not the purpose of this paper. Therefore, only some of the obtained data are given here, which should demonstrate the possibility of using the calculation-experimental method to predict the alloying element content in the solid solution in order to study such problems. From the data given in Figure 3–5, it is seen that increase of AF content in the weld metal structure is associated with increase of titanium content in the solid solution, and increase of the content of manganese and silicon leads to a change of the content of PF and WF, respectively.

These data correspond to the results of specialized research [8–10], which leads to the conclusion that the suggested calculation-experimental method provides an adequate assessment of both the level of solid solution alloying, and level of oxygen potential of the welding flux, at which the intensity of the processes of some alloying element dissolution in ferrite can be lowered to produce the specified morphology of weld metal structural components.

Method of prediction allowing determination of threshold value of oxygen potential of the flux at which solid solution alloying starts, enables estab-

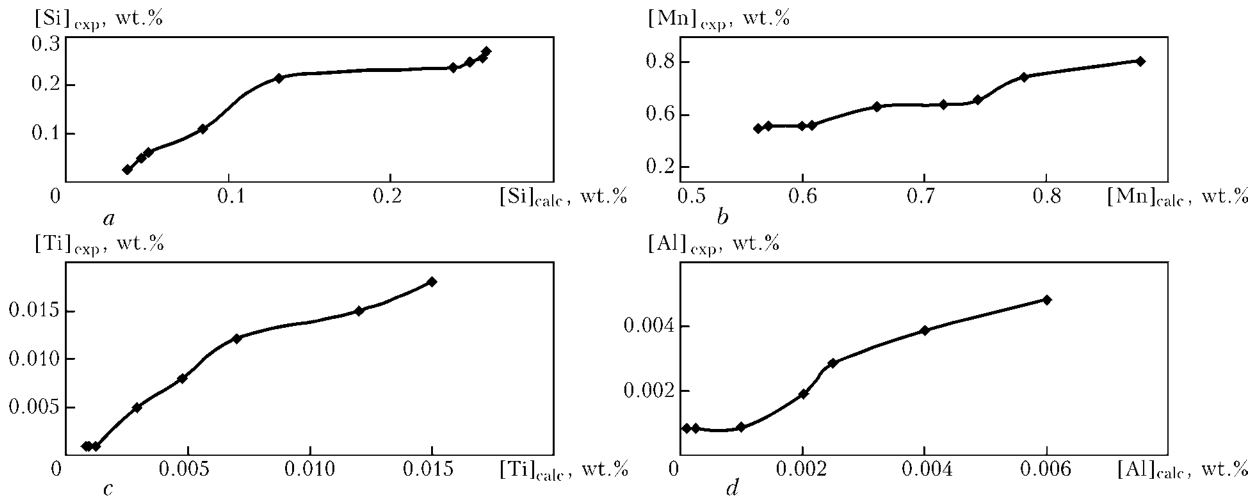

Figure 2. Comparison of calculated and experimental data on the silicon (*a*), manganese (*b*), titanium (*c*) and aluminium (*d*) content in the solid solution

Table 3. Content of microstructural components in deposited metal samples produced in welds using test fluxes

Sample No.	Volume fraction of structural component, %					
	PF	WF	AF	FOSP	FDSP	MAC-phase
3 / 1	15–20	9–11	31–37	14--15	24–27	5.4
3 / 4	15–18	9–12	25–34	16--27	20–23	5.0
3 / 7	15–20	6--7	30–40	24--25	20–27	3.4
2 / 1	13–20	3--5	40–45	17--20	23–25	4.0
2 / 4	13–20	3--9	46–49	13--19	16–18	5.0
2 / 7	13–23	5--9	43–46	13--18	6–14	2.3
1 / 1	6–12	2--4	50–55	16--27	17–21	2.5
1 / 4	5–12	3--5	48–50	12--25	32–37	3.5
1 / 7	4–10	1--3	44–50	11--15	36–38	2.4

Note. PF — polygonal ferrite; WF — Widmanstaetten ferrite; AF — acicular ferrite; FOSP — ferrite with ordered secondary phase; FDSP — ferrite with disordered secondary phase.

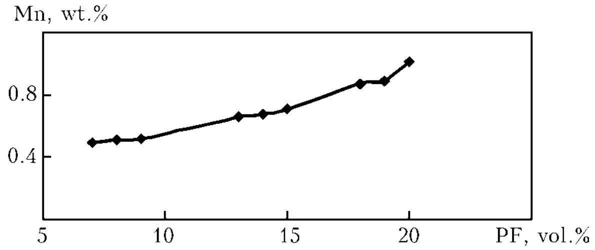

Figure 3. Interrelation between manganese content in the solid solution and content of polygonal ferrite PF in the weld metal structure

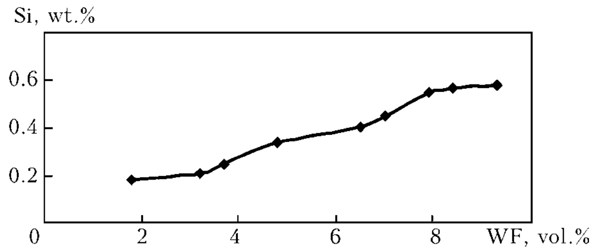

Figure 4. Interrelation between silicon content in the solid solution and content of Windmanstaetten ferrite WF in weld metal structure

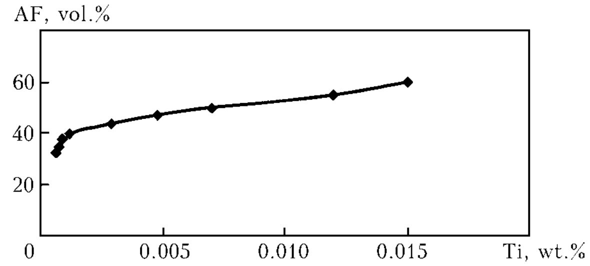

Figure 5. Interrelation between content of titanium in the solid solution and acicular ferrite AF in the weld metal structure

lishing the optimum level of weld pool deoxidation. Above this limit a large amount of non-metallic inclusions form in the weld metal, and the higher the oxygen potential of the flux, the higher will be the fraction of manganese and / or aluminium silicates in the composition of these inclusions. Such cases were considered in [5]. Below this limit the processes of ferrite alloying with aluminium and titanium start developing, and, as was shown in this study, the lower the oxygen potential of the flux, the higher is the level of this alloying.

This limit can be different for different flux compositions, depending on the level of requirements to welding-technological properties of the flux, its sanitary-hygienic characteristics, specified properties of the metal of welds and welded joints. Optimum level of deoxidation can be calculated based on computer simulation methods in the case of establishment of specific requirements to the amount and composition of non-metallic inclusions, level of mechanical properties of weld metal and respective AF fraction in their structure.

CONCLUSIONS

1. Based on computer simulation, a calculation-experimental method is proposed, which allows prediction of the level of ferrite matrix alloying.

2. Comparison of the results of calculations made by the proposed procedure with experimental results, demonstrated a good validity of the obtained predictions. Obtained results allow recommending the use of the proposed procedure both for calculation of the level of solid solution alloying, and for determination of the optimum level of oxidizing potential of welding consumables.

1. Povolotsky, D.Ya. (1970) *Aluminium in structural steel*. Moscow: Metallurgiya.
2. Lyakishev, N.P., Pliner, Yu.L., Lapko, S.I. (1985) *Titanium-containing alloy and steels*. Moscow: Metallurgiya.
3. Hannerz, N.E. (1980) The influence of silicon on the mechanical properties and on the weldability of mild and high tensile structural steels. Literature survey and own experimental studies. *IIW Doc. IX-1169–80*.
4. Ohkita, S., Horii, Y. (1995) Recent development in controlling the microstructure and properties of low alloy steel weld metals. *ISIJ Int*., 35(**10**), 1170--1182.
5. Golovko, V.V. (2001) Modelling of composition of non-metallic inclusions in weld metal of high-strength low-alloyed steels. *The Paton Welding J*., **5**, 2–6.
6. (1965) *Thermodynamic properties of inorganic materials*: Refer. Book. Ed. by A.P. Zefirov. Moscow: Atomizdat.
7. Pokhodnya, I.K., Frumin, I.I. (1955) About temperature of weld pool. *Avtomatich. Svarka*, **5**, 14--24.
8. *EN 1597–1*: Schweisszusaetzeruefung zur Einteilung. Teil 1: Pruefstueck zur Entnahme von Schweissen Stahl, Nickel und Nickellegierungen.
9. Evans, G.M. (1980) Effect of manganese on the microstructure and properties of all-weld metal deposits. *Welding J.*, 59(**3**), 67–75.
10. Evans, G.M. (1986) The effects of silicon on microstructure and properties of C–Mn all-weld metal deposits. *Metal Construction*, 18(**7**), 438–444.
11. Davis, M.L.E., Pargeter, R.J., Bailey, N. (1983) Effects of titanium and boron additions to submerged arc welding fluxes. *Ibid*., 15(**6**), 338–344.

INITIATION AND RE-DISTRIBUTION OF INTERNAL STRESSES IN ELECTRIC ARC COATINGS DURING THEIR FORMATION

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Electric arc flux-cored wire deposition of coatings results in formation of residual tensile stresses, which may cause initiation of cracks in the coatings, or their fracture, especially in finishing operations. It is shown that coating deposition parameters have a substantial effect both on the kinetics of formation of internal stresses, and on their residual level.

Keywords: electric arc spraying, coating, flux-cored wire, coating deposition parameters, internal stress, cohesion, split ring

Electric arc coatings sprayed from flux-cored wires (FCW) of the Fe–Cr–B–Al alloying system, characterised by wear resistance under boundary friction conditions, are widely applied in industry for rejuvenation of worn out shaft-type machine parts and protection of radiation tubes and economiser pipes of heat power stations from abrasive wear at normal and increased temperatures. Electric arc spraying of coatings from the FCW melts results in internal stresses forming in them, which may cause initiation of cracks and fractures, especially in finishing operations.

Coating deposition parameters have a substantial effect both on the kinetics of formation of internal stresses, and on their residual level. Coatings fracture mostly under the effect of stresses of the first kind, which are levelled in their bulk. The subject of our investigations is the effect of spraying parameters on formation of stresses and their residual value.

Experimental procedure. Internal stresses in coatings were evaluated by the split ring method (Figure 1) [1–3], which allows determination of stresses during the process of formation and cooling of the coatings to room temperature from variations in distance between the split ring ends. According to this method, extension rods *2* with internal slots, which reliably fix strain sensor *3* protected by screen *4*, are welded to the ends of split ring *1* 60 mm in diameter, 20 mm high and 4 mm thick. The coatings were deposited on the external surface of split ring *1* using FCW FMI-2. The speed of rotation of the ring in coating formation was 40 min^{-1} (Figure 2). Ferrochromium-boron FKhB-2 (60 %) and aluminium powder PA-40 (40 %) were used as materials of the FCW core. Diameter of FCW was 1.8 mm, and the core filling factor was 20 %.

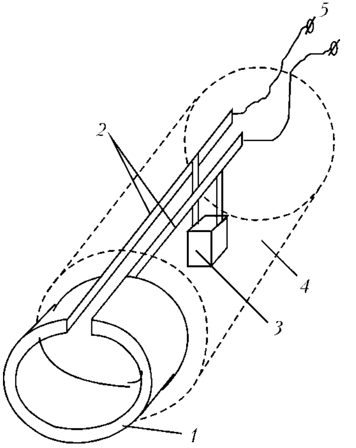

Figure 1. Schematic of measuring internal stresses in coating during its formation: *1* — split ring (sample); *2* — extension rods; *3* — strain sensor; *4* — protective screen; *5* — leads to instrument

Circumferential and radial stresses in a coating (Figure 3) were calculated from the following formulae [1]:

$$\sigma_c = r_2^2 p(1 + r_1^2/\rho^2)/(r_1^2 - r_2^2);$$

$$\sigma_r = r_2^2 p(1 - r_1^2/\rho^2)/(r_1^2 - r_2^2),$$

where r_1 and r_2 are the external and internal radii of a sprayed layer, respectively; p is the contact pressure formed by the coating; and ρ is the distance from the ring centre to a certain point.

Maximal circumferential stresses formed on the internal surface of a sprayed layer, which is in direct contact with the ring surface (at $\rho = r_2$), were calculated using the following formula from study [1]:

$$\sigma_c^{max} = p(r_1^2 + r_2^2)/(r_1^2 - r_2^2).$$

Radial stresses formed at any point of the surface (Figure 4) were $\sigma_r = -p$. Contact pressure p formed

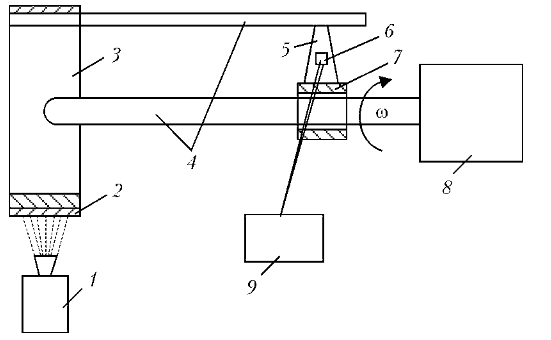

Figure 2. Schematic of measuring stresses in coating during its formation: *1* — electric arc metalliser; *2* — coating; *3* — split ring; *4* — extension rods; *5* — beam; *6* — strain sensor; *7* — casing; *8* — electric motor; *9* — recorder; ω — circumferential speed

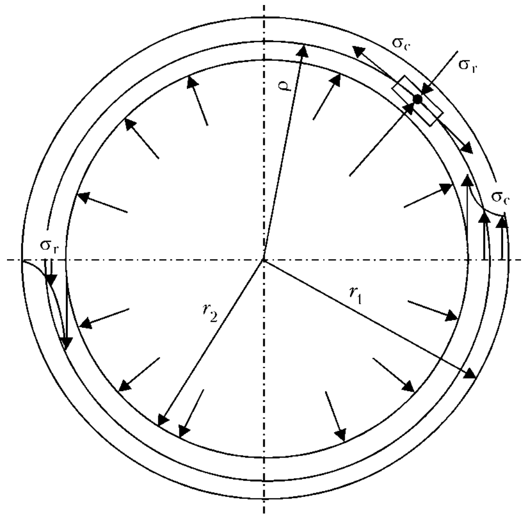

Figure 3. Schematic of distribution of stresses in sprayed coating layer [1]

under the effect of a sprayed layer was determined from the following expression:

$$p = E\Delta_{km} / (12r_m^4 / t^3)(\lambda + \mu) - (r_m^2 / t)(\eta - \mu),$$

where E is the elasticity modulus of the ring material; Δ_{km} is the width of a cut between the ring ends; $t = r_1 - r_2$ is the ring thickness; and r_m is the mean radius of the sprayed layer;

$$\lambda = \cos(\varphi_0 / 2)\ (3\pi - 1.5\varphi_0 + 2\sin\varphi_0 - 0.25\sin 2\varphi_0);$$

$$\mu = \sin(\varphi_0 / 2)\ (1 - \cos\varphi_0 + 0.5\sin^2\varphi_0);$$

$$\eta = \cos(\varphi_0 / 2)\ (-\pi + 0.5\sin\varphi_0 + 0.25\sin 2\varphi_0);$$

and φ_0 is the angle of opening of the ring after cutting.

Using the method we improved, it is possible to trace the level of internal stresses in a coating at all stages of formation of the latter, and optimise parameters of the electric arc metallising process, such as compressed air pressure, spraying distance and optimal thickness of the coating.

Formation of stresses in coating during its deposition. Variations in values of maximal circumferential stresses during the process of electric arc deposition of coatings (see Figure 2) were investigated on

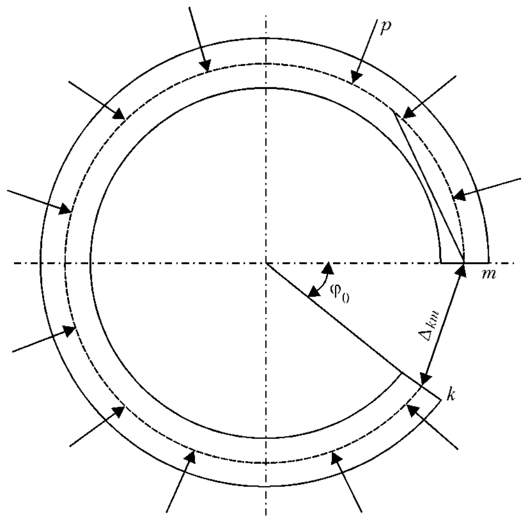

Figure 4. Schematic of formation of internal stresses during the process of deposition of coating on the external surface of the split ring [1]: *m*, *k* — end planes of the split ring

steel split rings, and variations in the width of cut, Δ_{km}, were continuously recorded. The electric arc metalliser was in a fixed position. Diameter of the spraying spot at a distance of 100 mm was 35 mm, and it fully covered the sprayed ring 20 mm wide, the speed of movement of the spraying spot on the perimeter of the ring at its rotation speed of 40 min^{-1} being 13 mm / s. It was established that the spraying process resulted in internal tensile stresses formed in the coatings, and that the stresses increased in spraying of the first layer (Figure 5). Deposition of the next layers leads to decrease in tensile stresses, as each next sprayed layer is deposited on the previous one at a higher temperature than that of the ring. Moreover, a spray material has a lower thermal conductivity, compared with the steel substrate. As a result, each next sprayed layer cools down slower, and lower tensile stresses are formed in it.

To determine the character of variations of stresses after spraying, the rings with coatings were cooled with quiescent and compressed (p = 0.6 MPa) air. It can be seen from Figure 5 that circumferential tensile stresses in coatings cooled with a compressed air increase in a jump-like manner because of rapid cooling of the surface layer. In cooling with a quiescent air the stepwise increase in stresses also takes place, but this increase is much lower.

In subsequent cooling of coatings to room temperature in a quiescent air, the presence of only residual tensile stresses is fixed. In sudden and rapid cooling with a compressed air the level of stresses is higher than in cooling with a quiescent air.

It is apparent that increase in time of continuous spraying results in a thicker coating. In this case the general temperature of the ring also increases. In a case of long-time continuous spraying, a jump of circumferential tensile stresses in a coating during cooling is higher, whereas the level of residual stresses is lower (Figure 6).

With increase in the arc power a thicker coating is formed within the same time. The ring temperature grows, and the jump of values of circumferential tensile stresses caused by cooling becomes much higher than in the case of a lower-power arc (Figure 7). And vice versa, residual stresses decrease with increase in the arc power.

Effect of spraying parameters on cohesion and residual stresses. For investigation purposes, the coatings were formed layer-by-layer using an electric arc metalliser moved in parallel with the spraying surface at a speed of 4.5 m / s (see Figure 2). Coatings 1 mm thick were formed in 10 passes.

It was established that increase in pressure of a spraying air from 0.35 to 0.80 MPa resulted in an increase in maximal circumferential tensile stresses from 3.5 to 8.0 MPa. At the same time, tensile strength of the coatings grows from 50 to 100 MPa (Figure 8). At a higher compressed air pressure the FCW melt is dispersed more intensively, and the velocity of molten particles grows, thus leading to increase in cohesion characteristics of a coating, as the rate of cooling of finely dispersed droplets (about 50 μm in size) is higher. At the same time, coatings formed from drop-

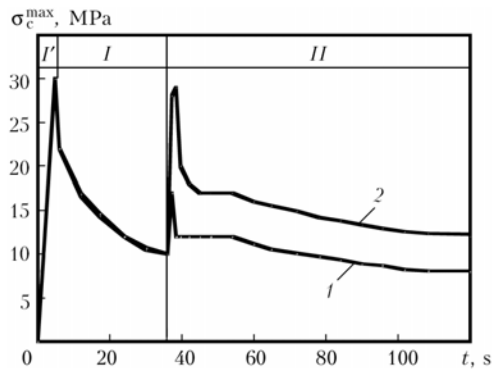

Figure 5. Variations in maximal circumferential stresses σ_c^{max} in coating of FCW FMI-2 during spraying (*I*), cooling (*II*) with quiescent (*1*) and compressed (*2*) air: *I′* — spraying of the first layer; U_a = 32 V; I_w = 150 A; p = 0.6 MPa; spraying distance L = = 100 mm

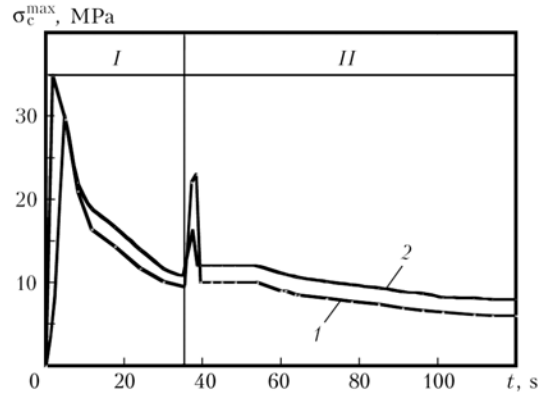

Figure 7. Variations in maximal circumferential stresses in coating of FCW FMI-2 at different power values: *I* — spraying; *II* — cooling in quiescent air; *1* — I_w = 100 A; *2* — 200 A (see the rest of the parameters in Figure 5)

lets of a larger size have the lower level of tensile stresses, and their relaxation lasts longer.

It was determined that residual stresses in a coating also depended to a considerable degree upon coating thickness δ. Thus, σ_c^{max} = 18 MPa at δ = 200 μm, and σ_c^{max} = 7 MPa at δ = 1000 μm. As each next sprayed layer in formation of coatings has a higher temperature than the previous one, thermal conductivity of the sprayed material is much lower than that of the substrate. Because of these two factors an increase in thickness of a coating is accompanied by growth of the contact temperature at the moment when a droplet hits against the surface. The coating cools down slower, and the stress relaxation process becomes more complete. Therefore, cohesion of each next layer grows, and, as a result, tensile strength of the entire coating increases. Tensile strength σ_t is 70 MPa at δ = 200 μm, and σ_t is 90 MPa at δ = 1000 μm (Figure 9).

When a coating is deposited on a body of revolution, this results in cyclic heating and cooling of its surface layers. Frequent heating and cooling cycles induce lower-level stresses in the coating.

It is shown that residual stresses in coatings are also affected by the spraying process productivity. At a higher spraying productivity, but at identical thickness of the coatings, the level of residual stresses formed in them is higher (Figure 10).

It is known that the most efficient method for increasing cohesion of coatings and lowering the level of residual tensile stresses in them is preheating of a workpiece immediately before spraying. Heating of a split ring to 250 °C leads to a decrease of 50 % in residual tensile stresses and increase in its tensile strength from 100 to 144 MPa (Figure 11), as droplets of the melt crystallise and cool down slower on a preheated substrate. As a result, relaxation of tensile stresses occurs more completely than in the cases where droplets crystallise on a cold substrate. At the same time, heating of the substrate leads to increase in temperature at the contact formed at impact by the droplet, and provides increase in adhesion of a coating.

Effect of preliminary and final shot blasting on the stressed state of coatings. As the technology for electric arc spraying of coatings includes preliminary shot blasting of the surface, the distribution of stresses in surface layers of a sprayed metal was determined after this treatment. Figure 12 shows that compressive stresses, the maximal values of which amount to 200 MPa on the coating surface, are formed deep to 200 μm in these layers.

The distribution of stresses through thickness of a coating after spraying is shown in Figure 13 (curve *1*). As seen from the Figure, tensile stresses are of the same value (about 12 MPa) through entire thickness. A sudden jump of compressive stresses (about 200 MPa) takes place at the coating–substrate interface, which is followed by their further decrease at a

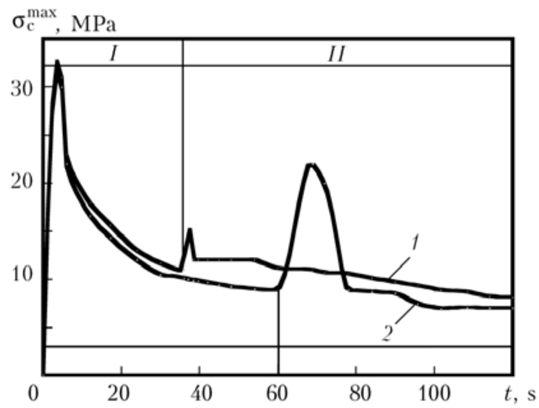

Figure 6. Variations in maximal circumferential stresses in coating of FCW FMI-2 during spraying for 30 (*1*) and 60 (*2*) s: *I*, *I′* — spraying process; *II*, *II′* — cooling in quiescent air

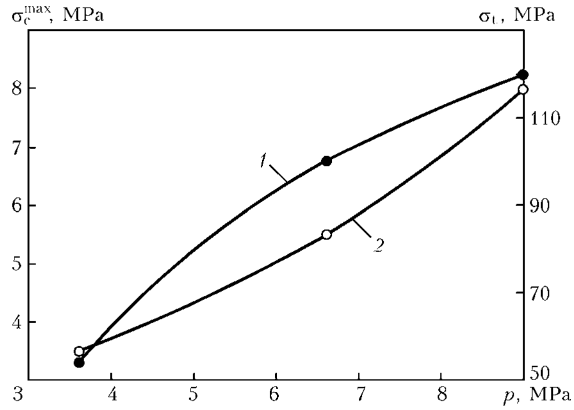

Figure 8. Effect of compressed air pressure on cohesion (*1*) and residual stresses (*2*): U_a = 32 V; I_w = 150 A; L = 100 mm; coating thickness δ = 1 mm

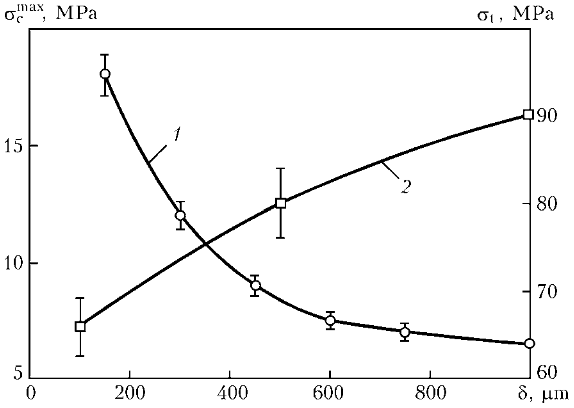

Figure 9. Effect of coating thickness δ on tensile residual stresses (*1*) and cohesion (*2*): I_w = 150 A (see the rest of the spraying parameters in Figure 5)

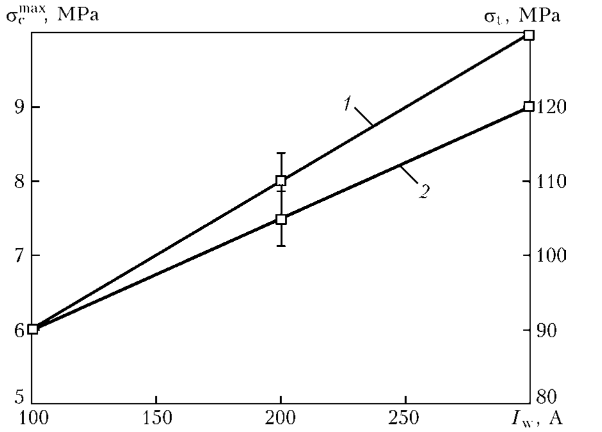

Figure 10. Effect of welding current I_w on cohesion (*1*) and residual stresses (*2*) in coating: U_a = 32 V; *p* = 0.6 MPa; *L* = 100 mm; δ = 1 mm

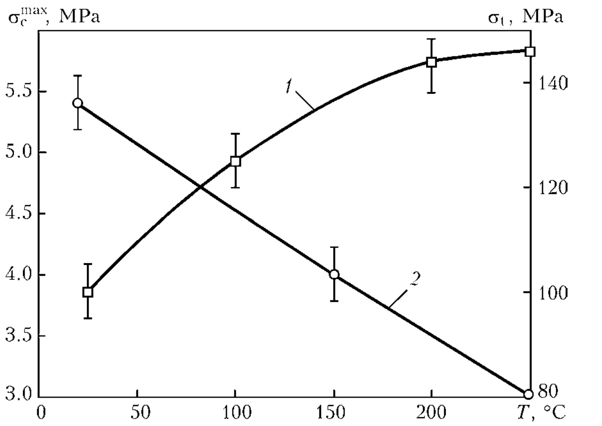

Figure 11. Effect of substrate heating temperature *T* on cohesion (*1*) and residual stresses (*2*) in coating: I_w = 150 A; δ = 1 mm (see the rest of the spraying parameters in Figure 10)

depth of 100 μm and subsequent transformation to tensile stresses.

To decrease tensile stresses in a sprayed layer, it was subjected to shot blasting with corundum (particle size 1--2 mm, *p* = 0.6 MPa, treatment time 30 s). Shot blasting was found to affect the sprayed layer like it affects a solid material, i.e. compressive stresses with a maximal value of 180 MPa on the coating surface are formed in the coating after its abrasive treatment with corundum (curve *2* in Figure 13). Under accepted conditions, the effect of this shot blasting shows up at a coating thickness of up to 150 μm, the

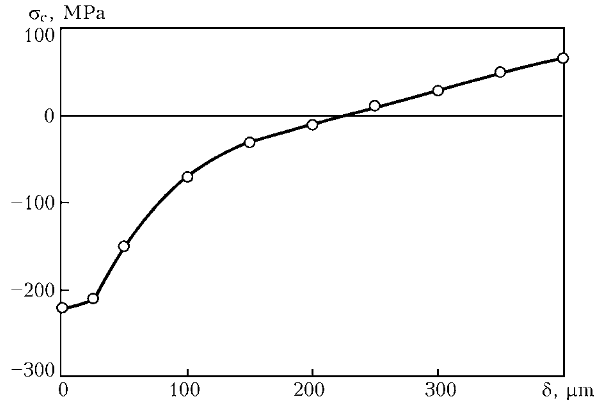

Figure 12. Distribution of stresses in surface layer of non-coated St.3 sample after shot blasting

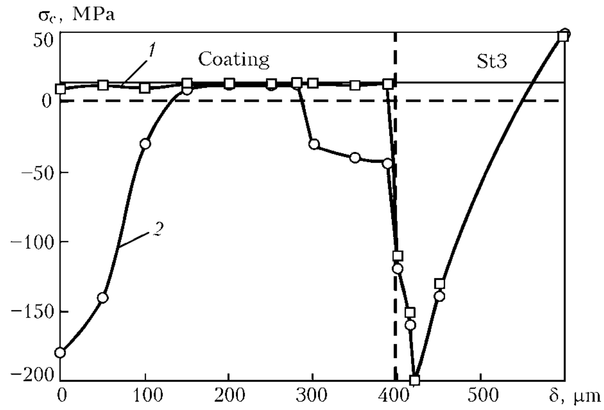

Figure 13. Distribution of stresses through thickness of coating of FCW FMI-2 without (*1*) and after (*2*) shot blasting

values of tensile stresses in treated and untreated samples being the same. In addition, the effect of this treatment propagates to a coating–substrate transition zone. Compressive stresses are also formed in a coating on the substrate side. This re-distribution of stresses leads to a substantial increase in cohesion of the coating, i.e. its strength grows from 100 to 135 MPa.

It can be concluded from an example of formation of electric arc coatings from FCW FMI-2 that investigation of the mechanisms of formation and re-distribution of internal stresses in coatings during their deposition is important for understanding the nature of the processes which determine subsequent performance of sprayed coatings. In particular, cooling of the coatings with a compressed air induces higher tensile stresses in them than cooling with a quiescent air. Increase in pressure of the compressed air also leads to growth of maximal circumferential tensile stresses. The level of tensile stresses can be substantially lowered, and strength properties of the coatings can be improved through preheating the metal substrate immediately before spraying, as well subjecting the coating surface after spraying to shot blasting.

1. Skvortsov, B.P., Sidorenko, Yu.A. (1984) Calculation of residual stresses in thermal sprayed layer. In: *Transact. of Belorus. Agricult. Acad*.
2. Student, M.M., Pikh, V.S. (1993) Dependence of residual stress level on coating composition and electric arc metallization conditions. *Fiziko-Khimich. Mekhanika Materialiv*, **5**, 46–52.
3. Pokhmursky, V.I., Student, M.M. (1998) Formation and redistribution of internal stresses in coatings during their deposition. *Mat. Metody ta Fizyko-Mekhanichni Polya*, **2**, 105–108.

LOWERING OF MATERIAL CONTENT OF POWER SOURCES AND POWER CONSUMPTION IN WELDING

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Experience of employing pulsed devices for arc stabilization in AC manual arc welding, ensuring a high stability of the welding process and quality of weld formation, and saving of electrical engineering materials in manufacture of welding transformers and of power in their operation, is described.

Keywords: arc welding, welding transformer, alternating current, welding process stability, power saving, electrical engineering materials

Wide acceptance of coated-electrode manual arc welding stimulates the improvement of materials and equipment, designed for this welding process. As regards equipment, power sources should be improved first of all. Inverter-type power sources have become accepted now as a promising class of welding equipment. However, the sophistication of their electric circuit and high cost make a poor combination with the simplicity of the design and comparatively low cost of the holder and electrodes for manual arc welding. In this connection, the problems of reducing the weight and power consumption of the sources, development of their portable variant are important and urgent for arc welding. One of the promising directions, in our opinion, is application of a pulsed device of arcing stabilization (PDAS) in combination with AC power sources, namely welding transformers. PDAS is an instrument consisting of connected in series power winding, capacitor, thyristor switch and arc gap (welding winding). Capacitor discharge at each transition of welding current through zero promotes re-striking of the arc. There exist the following capabilities for widening the scope of alternating welding current application:

- use of PDAS with batch-produced welding transformers;
- lowering of transformer open-circuit voltage, $U_{o.c}$ through the use of PDAS;
- development of combined transformers with thyristor control and PDAS;
- development of multi-operator AC welding systems with PDAS in the stations.

Let us consider these capabilities in greater detail.

1. Effectiveness of PDAS connection to a welding transformer was evaluated [1] by comparative testing of a standard welding transformer of TDM-503 type with PDAS and without it. PDAS of SD-3 type was used in this case. To ensure welding with electrodes designed for direct current, the most favourable conditions were created for TDM-503 transformer without PDAS, namely mains voltage was somewhat increased, and welding mode was selected at the first stage of current adjustment, when induction of the transformer magnetic core steel is not higher than the admissible one, as the transformer primary and secondary windings are connected in series (sinusoidal voltage curve is not distorted at its output, as in the case of parallel connection, i.e. the rate of voltage rise after transition through zero is high enough [2]). Thus, this transformer windings have a low ohmic resistance of welding circuit R_c and its ratio to reactive resistance X_c is negligible: $\gamma = R_c / \gamma_c \approx 0$.

PDAS connection to the welding transformer led to improvement of practically all the indices given in Table 1. This is noticeable in welding with electrodes designed for direct current: metal losses (coefficient of losses K_l) are decreased particularly in welding with electrodes with refractory coatings; a tendency to increase of the deposition coefficient a_d and electrode melting rate v is observed, total index B of the transformer welding properties determined to GOST 25616–83 increases [3]. In addition, PDAS application allows welding of critical items to be performed by a less skilled welder, facilitates his work, improves weld formation quality, promotes power saving and improves the efficiency of the welding process, enables applying more efficient modes and electrodes, increasing the arcing time fraction in the overall working time of the welder. On the other hand, cost of PDAS of 0.4 kg weight is not more than 5–7 % of the transformer average cost. Considering that the annual output of welding transformers is equal to many thousand units, and there already exists a considerable fleet of them, one can just anticipate the saving of funds provided by PDAS application.

2. Lowering of open-circuit voltage, $U_{o.c}$, of the welding transformer leads to reduction of its weight and dimensional characteristics in fabrication, as well as improvement of safety of the operating conditions.

We, however, cannot ignore the fact that related to $U_{o.c}$ are the arcing stability characteristics, possibility of ensuring such parameters of the specified operating mode as arc voltage and welding current. Initial arc striking in manual welding is performed by shorting the electrode on the item; after each transition of welding current through zero, it is necessary to provide sufficient re-striking voltage U_{str} for re-igni-

Table 1. Results of testing TDM-503 transformer with and without PDAS

Electrode grade	d_e, mm	I_2, A	U_2, V	TDM-503U2			
				K_1, %	à$_d$, g / (À·h)	v, mm / (À·h)	B, points
UONI-13 / 55	5	220	24	7.37	8.71	1.59	19
UONI-13 / 45	4	140	22	3.01	8.58	2.38	21
OZL-8	4	120	25	5.43	12.50	3.26	17
MR-3	4	210	23	10.40	7.73	2.30	20
ANO-4	4	195	24	12.40	8.72	2.67	22
	3	120	25	10.90	8.62	4.67	22

Table 1 (cont.)

Electrode grade	TDM-503 +SD-3				α_1, %	α_2, %	α_3, %	α_4, %
	K_{10}, %	à$_{d0}$, g / (À·h)	v_0, mm / (À·h)	B_0, point				
UONI-13 / 55	5.50	8.90	1.67	22	25	2.2	5	16
UONI-13 / 45	1.88	8.80	2.54	24	38	2.6	7	14
OZL-8	5.08	12.90	3.95	20	6	3.2	21	18
MR-3	7.44	8.01	2.40	22	29	3.6	4	10
ANO-4	12.30	8.94	2.75	22	1	2.5	3	0
	9.63	8.81	4.93	23	12	2.2	6	4

Notes. 1. d_e — electrode diameter; I_2, U_2 — current and voltage of secondary circuit, respectively; $\alpha_1 = [(K_{10} - K_1) / K_1]\cdot 100$ %; $\alpha_2 = [(a_{d0} - a_d) / a_d]\cdot 100$ %; $\alpha_3 = [(v_0 - v / v]\cdot 100$ %; $\alpha_4 = [(B_0 - B / B]\cdot 100$ %; for the rest see the text. 2. Tests were conducted at $U_{o.c} = 83$ V.

tion of the arc. The higher U_{str} (for electrodes at alternating current — 40–50 V; at direct current — 60–90 V and higher), the higher should be $U_{o.c}$ value.

With decrease of open-circuit voltage, U_{str}, arc striking voltage, U_{str}, is usually only slightly increased at the change of current polarity. However, at random disturbances of arc length, welding mode, thermal condition of the arc column (due to metal transfer, lip formation on the electrode, etc.), U_{str} becomes greater at low values of $U_{o.c}$ than at its high values, particularly, if the value of effective ionization potential of the arc gas is high. In this case, U_{str} will be the higher, the longer does the random disturbance exist. Despite the fact, that the average frequency of random disturbances is much lower than that of alternating current of industrial frequency, these disturbances can cause a violation of the welding process stability. Thus, increase of $U_{o.c}$ of welding transformers is a means of overcoming random increases of U_{str} value, i.e. basically, a surplus of expensive active materials (electrical engineering copper and steel) is incorporated into the power source for the case of development of a disturbance, which may lead to an undesirable rise of U_{str}. Such a method of increasing the stability of the welding process is not cost-effective. Investigators have been trying for a long time to find more effective solutions, the best of which is connection of a pulse generator in parallel to the arc, providing the necessary value of U_{str} at arc extinguishing.

PWI developed a new generation of PDAS, which are simple, cost-effective and reliable in operation. PDAS application enabled lowering $U_{o.c}$ values of the welding transformer. Investigations have been conducted [4] to determine the admissible limit of lowering of transformer $U_{o.c}$ values in manual arc welding with coated electrodes of different grades, including those designed for direct current welding. Investigation results showed [4] that in manual arc welding at up to 200 A current, $U_{o.c}$ value of the transformer should not be higher than 37 V, at up to 300 A current $U_{o.c}$ is < 45 V, and at up to 500 A current $U_{o.c}$ is < 55 V. On the other hand, $U_{o.c}$ of welding transformers designed for all the rated currents, is usually equal to 60–80 V.

It is known that change of the kind of current (for instance, in the case of UONI-13 / 45 electrodes) may affect the mechanical properties of welded joints. It was assumed that the values of these properties depend to a certain extent on the shape of the current and arc voltage curves, which change depending on $U_{o.c}$. Test welding of butt joints of sheet steel St3sp was conducted with application of a transformer with decreasing $U_{o.c}$. In this case, a special welding transformer with a flat external characteristic was used, providing an incremental (after 3–5 V) change of $U_{o.c}$ values from 30 to 80 V. The slope of the external characteristic was adjusted using a choke with a mobile shunt connected into the welding circuit in series. In addition to a pilot sample of the transformer, a standard STSh-500 transformer ($U_{o.c} = 60$ V) was tested, with PDAS designed for 100 Hz frequency being connected to it in parallel similar to the case of the pilot transformer. Electrodes of two types — UONI-13 / 45

Table 2. Indices of electrode melting and its energy parameters

Test No.	Electrode grade (diameter, mm)	Power source	$U_{o.c}$, V	I_1, A	U_1, V	P_a, kV·A	I_2, A	U_2, V	K_l, %
1	UONI-13 / 55 (5)	Test	36.5	25.0	384	5.20	215	22.0	11.90
2			37.0	23.5	389	4.74	195	22.5	7.18
3			36.5	23.0	385	4.40	185	22.0	2.11
4		STSh-500	60.0	34.0	384	5.14	200	23.0	3.70
5			60.0	38.5	380	5.60	215	22.5	2.37
6	MR-3 (4)	Test	36.5	24.0	384	5.00	195	24.0	11.80
7			37.0	23.0	388	4.44	180	23.0	9.96
8		STSh-500	60.0	32.7	384	5.22	195	24.0	16.10
9			60.0	36.0	384	5.28	195	24.0	13.20

Table 2 (cont.)

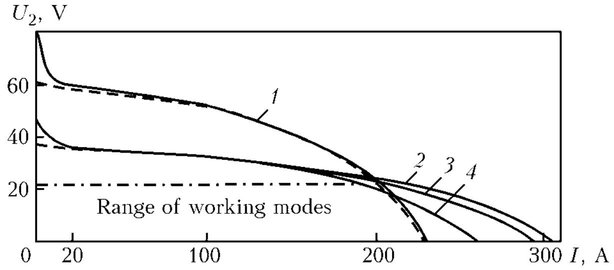
Test No.	Electrode grade (diameter, mm)	Power source	K_{d1}, g / (À$_2$·h)	K_{d2}, g / (Â$_1$·À$_1$·h)	Efficiency, %	cos φ	P_m, kV$_1$·À$_1$	Curves in the Figure
1	UONI-13 / 55 (5)	Test	8.90	0.200	91.0	0.54	9.60	*2*
2			9.44	0.201	91.6	0.54	9.14	*3*
3			10.10	0.211	92.5	0.50	8.86	*4*
4		STSh-500	9.95	0.152	89.5	0.39	13.10	*1*
5			10.00	0.147	86.4	0.38	14.63	*1*
6	MR-3 (4)	Test	7.37	0.156	93.6	0.54	9.22	–
7			7.49	0.156	93.2	0.50	8.92	—
8		STSh-500	7.32	0.114	89.7	0.41	12.56	—
9			7.38	0.104	88.6	0.38	13.82	—

Notes. I_1, U_1 — current and voltage of primary mains; P_a — active power of the transformer; $P_m = I_1U_1$ — power drawn from the mains; cos φ — power coefficient; K_{d1} — coefficient of deposition characterizing metallurgical properties of the electrode; K_{d2} — coefficient of deposition characterizing consumption of power drawn from the mains for melting a unit of electrode metal mass.

(with a basic coating) and MR-3 (with a rutile coating) were mainly used in the tests. Stability of the welding process was evaluated proceeding from the number of interruptions of arcing during the time of the entire electrode melting, as well as by the current and arc voltage oscillograms. Current was selected depending on electrode diameter (somewhat lower than the recommended value), $U_{o.c}$ was successively lowered up to appearance of at least one interruption of arcing, and such value of $U_{o.c}$ was regarded to be critical, i.e. inadmissible. For the above, as well as other grades of electrodes of 3, 4 and 5 mm diameter, the admissible limit of $U_{o.c}$ value lowering was 36–37 V. At a lower $U_{o.c}$ value, interruptions of arcing were observed, the number of which increased abruptly with $U_{o.c}$ lowering. Testing results indicate [4] that mechanical properties of the joints obtained at lower $U_{o.c}$, fully satisfy the requirements of GOST 9467–75 and are on the level of typical values for the given electrode grade. Thus, in terms of mechanical properties of welded joints, lowering of transformer $U_{o.c}$ values to 36–37 V is quite admissible.

Table 2 gives the indices of electrode melting and their energy parameters. As follows from Table 2, values of efficiency, cos φ and K_{d2}, corresponding to working modes in the case of the power source with low $U_{o.c}$ are greater, and the mains power P_m is lower than that of a source with high open-circuit voltage ($U_{o.c}$ = 60 V). Let us compare the results of tests 3 and 5, as well as 7 and 9 (Table 2). In the first case, at practically the same K_{d1} (10.1–10.0 g / (A$_2$·h) the transformer with a lower open-circuit voltage ($U_{o.c}$ = = 36.5 V) draws P_m = 8.86 kV$_1$·A$_1$ from the mains, and for a transformer with $U_{o.c}$ = 60 V — P_m = = 14.63 kV$_1$·A$_1$, i.e. by 40 % less than for the second one. In addition, the energy drawn from the mains in the first case is used in a more rational manner than in the case of a transformer with higher $U_{o.c}$ value. For deposition of the same mass of electrode metal the consumption of active power in test 3 is equal to 4.4 kW, and in test 5 — 5.6 kW, i.e. it is by 21 % higher. Coefficient of deposition K_{d2} shows that with $U_{o.c}$ lowering the deposited metal mass per 1 kW$_1$·A$_1$ of power consumed from the primary mains, increases by 40 %. Similar data were obtained also in tests 7 and 9: mass of deposited metal per 1 kV·A$_1$ of power drawn from primary mains also increases by 40 %.

Table 2 gives the melting indices K_d and K_l in welding with UONI-13 / 55 electrodes at different currents. A tendency is found to increase of coefficient



External characteristics of transformers in the field of working modes: *1* — STSh-500 ($U_{o.c}$ = 60 V, I_2 = 200–215 A); *2* — test transformer ($U_{o.c}$ = 36 V, I_2 = 215 A); *3* — same (I_2 = 185 A); *4* — same (I_2 = 185 A); solid curves — with PDAS connected in parallel to arc; dashed — without PDAS

of deposition K_d and lowering of the losses coefficient K_l, the values of which at 185 A current do not exceed those obtained for a transformer with $U_{o.c}$ = 60 V. Increase of the coefficient of deposition is related to lowering of welding current and short-circuiting current $I_{sh.c}$, respectively. Transformer with low values of $U_{o.c}$ has more flat external characteristics in the range of working modes than that with high $U_{o.c}$. In this case, out of three of its external characteristics (see curves *2*–*4* in the Figure) for the above welding modes (215, 195 and 185 A, respectively), curve *4* is the closest as to $I_{sh.c}$ value to that of transformer with $U_{o.c}$ = 60 V (curve *1*). Accordingly, the values of the coefficient of metal losses K_l are also close in this case. This leads to the conclusion that transformers with smaller $U_{o.c}$ values with PDAS can be used for welding in lower parameter modes.

Thus, a transformer with $U_{o.c}$ = 37 V fitted with PDAS, operating at the frequency of 100 Hz, provides coated-electrode welding at a current of about 200 A (both at alternating and direct current); this is also accompanied by saving of the material and power resources.

Proceeding from the conducted studies, PWI developed a combined arc welding transformer of TDK-315 type with PDAS ($U_{o.c}$ = 45 V; rated current I_r = = 315 A). PDAS built into it generated two pulses per a half-period. Comparison of its technical characteristics with those of a batch-produced transformer of TDM-317 type (Table 3) shows that in view of an increase of the coefficient of transformation in TDK-315, the rated primary current decreases, and in order to produce the rated arc power P_{2r} = 10.27 kW, it draws the power P_m = 17.6 kV$_1$·A$_1$ from the mains. To provide the same arc power, TDM-317 transformer ($U_{o.c}$ = 65 and 80 V) draws 22.5 kV$_1$·A$_1$ from the mains, i.e. consumes by 4.9 kV$_1$·A$_1$ (by 22 %) more energy than TDK-315. Having higher efficiency and cos φ, the proposed power source uses the consumed power in a more rational way. Each thousand of transformers with lower $U_{o.c}$ will draw from the mains by 4–5 ths kV·A less that those with $U_{o.c}$ = 60 V and more. Many hundred thousand welding transformers are now operating in Ukraine and this effect is obvious.

TDK-315 with LD = 60 % has the weight of not more than 85 kg (Table 3), i.e. saving of electrical engineering materials compared to TDM-317 analogue is about 35 %. In addition, TDK-315 transformer by its welding-technological properties is superior to the arc welding transformer with mechanical adjustment of TDM-317 type, as it allows welding to be performed with DC electrode. The cost of introducing PDAS will be covered just owing to reduction of TDK-315 weight.

Mock-ups of portable power sources for manual arc welding were developed on the basis of transformers with lower $U_{o.c}$ and PDAS designed for 100 Hz. «Razryad-90» power source of 18 kg weight (Table 4) developed at PWI, can be given as an example, which even though it is somewhat inferior to the inverter

Table 3. Comparative technical and power characteristics of TDM-317 and TDK-315 types

Parameter	TDM-317	TDK-315
Mains voltage U_1, V	380	380
Rated welding current I_{2r}, A	315	315
Relative load duration LD at 5 min cycle, %	60	20; 60
Primary current at rated welding current I_{1r}, A	58	42
Range of welding current adjustment, A:		
I_{2min}	60	100
I_{2max}	370	345
Open-circuit voltage of welding winding $U_{o.c}$, V	65; 80	45±4
Rated working voltage U_{2r}, V	32.6	32.6
Maximum working voltage U_{2max}, V	34.8	33.8
Rated power of welding arc provided by transformers $P_{2r} = I_{2r}U_{2r}$, kW	10.27	10.27
Efficiency at rated current $\eta = P_{2r} / P_1$, %, not less than	83	78
Power factor $\cos \varphi = P_1 / P_{1r}$	0.55	0.75
Rated consumed power from the mains $P_{m.r} = I_{1r}U_1$, kV·A, not more than	22.5	17.6
Weight Q, kg, not more than	130	55; 85

Table 4. Technical characteristics of batch-produced "Razryad" transformers developed at PWI

Power source	U_1, V	$U_{o.c}$, V	U_r, V	I_r, À	I_{min}–I_{max}, A	LD, %	f, Hz	m	Q, kg
TDM-401	380	63–80	36	400	80–460	60	–	2	145
TDE-402	380	80	44	400	80–400	60	–	1	180
TDM-315	380	63–80	33	315	60–360	60	–	2	130
«Razryad-315»	380	45	33	315	60–360	60	200	1	90
«Razryad-90»	220	40	24	90	30–95	20	100	1	18

Note. I_{min}–I_{max} — range of welding current adjustment; f — frequency of stabilizing pulses; m — number of current adjustment stages.

power source as to specific eight, is superior to it as to simplicity, reliability and low cost.

The idea of pulse ignition of the arc is used also in development of a number of ingenious welding power sources of not only alternating, but also direct current [5].

3. Development of thyristor-controlled transformers with PDAS is another method to improve the cost-effectiveness of welding equipment. PWI developed a thyristor-controlled arc welding transformer TDT with PDAS. It has the primary welding winding ($U_{o.c}$ = 45–55 V), depending on the rated current which is equal to 200–500 A, and connected in series additional winding and choke ($U_{o.c}$ = 35–25 V) for powering the pilot arc. Additional winding with a choke connected in series is shunted by the thyristor key. With the closed thyristors, the arc is powered by the total voltage of the welding and additional winding ($U_{o.c} \leq 80$ V), and current (25–50 A) of such a pilot arc is determined mainly by the value of the choke inductance. With open thyristors the current is determined by the rated value, for which the welding winding is designed.

Table 5 gives the technical characteristics of AC power sources designed for rated current of 250 and 315 A and a comparison of developed at PWI «Razryad-250» transformers with TDT-251 (I_r = = 250 A, LD = 20 %), as well as TDT-315 with batch-produced TDM-317 transformer (I_r = 315 A, LD = = 60 %). «Razryad-250» and TDM-317 transformers have open-circuit voltage $U_{o.c} \leq 60$ V, and TDT-251 and TDT-315 — $U_{o.c}$ = 45 and 50 V, respectively. From the Table it is seen that TDT-251 transformer, while ensuring the welding arc rated power P_{2r} = 7.5 kW, which is the same as that for «Razryad-250» transformer, draws 30 % less power from the mains for that, moreover, its weight is 10 % smaller. TDT-315 transformer also consumes 30 % less power from the mains, and its weight is 30 % less than that of TDK-317. TDT type transformers have one expanded range of welding current adjustment.

From Table 6 it is seen that TDT-251 transformer having $U_{o.c}$ = 45 V, will melt by 39 % (4 mm ANO-6 electrodes) and by 27 % (5 mm UONI-13 / 45 electrodes) more metal per 1 $A_1 \cdot V_1 \cdot h$ of power drawn from the mains than «Razryad-250» transformer with $U_{o.c}$ = 60 V. For deposition of 1 g of the metal, TDT-315 transformer ($U_{o.c}$ = 50 V) draws 45 % less power from the mains than TDT-317 transformer ($U_{o.c}$ = = 80 V).

Transformers of TDT type not only are not inferior in their welding and technological properties to the best local and foreign analogs, but are even superior to them, as they are suitable for welding with electrodes with a basic coating (UONI-13 / 45, OZL-8, etc.), nonconsumable electrode argon-arc welding of stainless steels, aluminium and its alloys.

4. Development of multi-station power supply systems is an important task of increasing the cost-effectiveness of welding fabrication. At concentration of a large quantity of welding power sources (rectifiers, transformers) on comparatively limited areas of enterprises, certain difficulties arise, which lower the labour efficiency and increase welding operation cost. Single-station welding transformers for 500 A current (TD-500U2, TDM-503U2, etc.) became widely accepted by industry, being usually used for currents of up to 300–350 A, inclusive. In the case of their considerable concentration in the shop premises, the production areas are not used in a rational manner. In the course of the work day, these sources are usually loaded by not more than 50 %. In addition, transformer operation with an open circuit leads to high power losses. Under such conditions the transformers are usually connected to the mains by 20–30 m power cables, which are laid on welded structures and assembly fixtures, which is undesirable in terms of safety. The transformers are connected to 380 V mains through switchboards in groups, and disconnection or connection of at least one of the stations leads to downtime of all the others.

In DC welding these drawbacks are eliminated due to the use of multi-station systems, which became widely accepted both in coated-electrode manual arc welding, and in mechanized CO_2 and submerged-arc welding, for instance with application of VMG-5000 rectifier for I_r = 5000 A. Transition from individual power sources to multi-station systems turned out to be rational in terms of overall saving of power and production areas, as well as reducing the cost of depreciation, maintenance and repair.

Unfortunately, the advantages of multi-station AC power supply have not yet been realized in practice. The main cause for that is absence of an engineering solution, ensuring a reliable and cost-effective operation of the system. Use of the existing engineering

Table 5. Specification of welding transformers

Parameter	«Razryad-250»	TDT-251	TDM-317	TDT-315
Mains voltage U_1, V	380	380	380	380
Rated welding current I_{2r}, A	250	250	315	315
Relative load duration LD at 5 min cycle, %	20	20	60	60
Primary current at rated welding current I_{1r}, A	43	31	65; 43	42
Range of welding current adjustment, A:				
I_{2min}	90	25	60	25
I_{2max}	255	275	340	375
Open-circuit voltage of welding winding $U_{o.c}$, V	60±4	45±4	65; 80	50±4
Open-circuit current $I_{1o.c}$, A, not more than	4	4	6	4
Rated working voltage U_{2r}, V	30.0	30.0	32.6	32.6
Maximum working voltage U_{2max}, V	30.2	31.0	33.6	35.0
Rated power of welding arc P_{2r} provided by the unit, kW	7.5	7.5	10.3	10.3
Maximum power of welding arc P_{2max} provided by the unit, kW	7.7	8.53	11.424	13.125
Efficiency at rated current η, %, not more than	75	83	80	86
Power factor cos φ, not less than	0.65	0.84	0.56	0.75
Rated power drawn from the mains P_{1r}, $kV_1 \cdot A_1$, not more than	15.4	10.8	23.0	16.0
Maximum power drawn from the mains P_{1max}, $kV_1 \cdot A_1$	15.8	12.23	25.5	20.35
Set maximum consumed power $P_{s\,max}$, kV·A, not more than	17.4	13.5	28.1	22.4
Pulse repetition rate f, Hz	100	100	--	100
Time of PDAS switching off in transformer open-circuit mode τ, s, not more than	2	2	--	2
Overall dimensions, cm:				
length	35	35	52	50
width	31	31	58	45
height	47	47	80	50
Weight Q, kg, not more than	50	45	130	90

Note. LD = $(\tau_w / \tau_c) \cdot 100$ %; $U_{2r} = 20 + 0.04 I_{2r}$; $U_{2max} = 20 + 0.04 I_{2max}$; $P_{2r} = I_{2r} U_{2r}$; $P_{2max} = I_{2max} U_{2max}$; $\eta = P_{2r} / P_1$; $\cos \varphi = P_1 / P_{1r}$; $P_{1r} = P_{2r} / \eta \cos \varphi$; $P_{1max} = P_{2max} / \eta \cos \varphi$; $P_{s\,max} = 1.1 P_{1max}$.

solutions for multi-station systems operating at direct current, does not yield any positive result, as current adjustment in the stations using a ballast rheostat does not ensure the required stability of the process, or reliability of arc striking and involves high power losses.

The engineering solution for a multi-station system for AC welding proposed by PWI [5], is based on application of a powerful welding transformer with a flat characteristic with connection of welding stations to it, each of which is a compact adjustable choke fitted with PDAS. PDAS built into the welding transformer can also be used, but in this case their power supply should be envisaged (50 V). Finally, a multi-station system can be designed by the principle of the above thyristor-controlled transformers with PDAS developed at PWI: a common transformer for the stations with a flat external characteristic and individual thyristor regulator in each station with the pilot arc transformer.

Table 6. Coefficients of melting K_d, K_l, a_d and total index B of welding properties of the compared transformers

Power source	Electrode (dia., mm)	$U_{o.c}$, V	I_1, À	U_1, V	I_2, À	U_2, V	K_l, %	à$_d$, g / (À$_2$·h)	K_d, g / (V$_1$·À$_1$·h)	B, points
«Razryad»	ANO-6 (4)	60	34	378	190	25	8.40	8.80	0.128	23
	UONI-13 / 45 (5)	60	35	378	188	24	3.70	3.37	0.134	24
TDT(UDS)-251	ANO-6 (4)	45	25	374	180	25	7.90	8.22	0.178	22
	UONI-13 / 45 (5)	45	26	372	200	26	3.10	8.91	0.183	20
TDK-315	ANO-6 (4)	45	24	375	180	25	8.20	9.10	0.188	23
	UONI-13 / 45 (5)	45	24	378	188	23	2.60	9.50	0.197	24
TDM-317	ANO-6 (4)	82	45	372	210	24	9.07	7.90	0.100	24

Table 7. Specification of power sources for multi-station systems

Parameter	TDM-503	TDF-1601	TDEM-1201	TDEM-3001	TDEM-501
Rated welding current I_r, A	500	1600	1200	3000	500
Rated working voltage U_r, V	40	70	60	70	40
LD, %	0.6	1.0	1.0	1.0	1.0
Open-circuit voltage $U_{o.c}$, V	65 (80)	75	65	75	55
Efficiency	0.86	0.88	0.92	0.92	0.90
Power factor cos φ	0.65	0.90	0.92	0.92	0.90
Open-circuit power losses $P_{o.c}$, kW	1.5	2.0	2.0	2.0	1.0
Rated consumed power P_r, kV·A	21.47	141.4	85.0	248.0	24.7
Number of power sources N in 48 stations, pcs	48 / 48	2 / 48	3 / 48	1 / 48	1 / 4
Area taken up by multi-station system S_s, m^2	57.4 (1.2)	16 (0.33)	12 (0.25)	9 (0.19)	1.44 (0.36)
Weight of one power source Q_s, kg	170	1000	800	2300	250
Weight of one choke Q_{ch}, kg, not more than	–	60	50	50	50
Weight of multi-station system, kg, not more than	8160 (170)	4880 (102)	4800 (100)	4700 (98)	450 (112)
Relative weight of the system Q_n / Q_b	1.00	0.60	0.59	0.58	0.66
Relative wholesale cost of 48 stations (or four stations for TEDM-500) C_n / C_b	1.00	0.59	0.60	0.40	0.70

Notes. 1. C_n ---- new price of multi-station system; C_b ---- same for basic variant. 2. The area and weight calculated for one station are given in parenthesis; rated power of one power source $P_r = (U_r I_r \mathrm{LD}) / (\eta \cos \varphi)$.

As is known, an important stage in introducing a new engineering solution is its cost study. This requires comparing the new solutions with the existing ones.

To check the proposed engineering solution under production conditions, batch-produced welding transformers TDF-1001 and TDF-1601 were modified in such a way that their external static characteristic were close to the flat one (primary and secondary windings are as close as possible, the shunt is removed, etc.). For these transformers also a welding current regulator of OI-125 UKhLZ type was developed, which services four stations and consists of four chokes with smoothly adjustable (by a magnetic shunt) inductance. A PDAS is connected to each choke.

PWI manufactured mock-ups of TDEM-1200U4 and TDEM-3000U4 transformers with flat external characteristics designed for current of 1200 and 3000 A. Let us compare the multi-station systems of AC power supply for 48 and for 4 stations based on sources given in Table 7.

The first system (basic variant) consists of self-sufficient welding transformers of TDM-503 type (48 pcs) and let us take the relative weight of this

Table 8. Operating modes of four-station system

Technology variant No.	Number of stations n, pcs	Modes of station operation (β = 0.6)	Power	Transformer power, kW	
				TDM-503	TDEM-501
1	1	I = 500 A U = 40 V	$Đ_r$ $Đ'$ $P'_{o.c}$	21.47 3.00 0.60	14.81 1.48 0
2	1	I = 315 A U = 31.6 V	$Đ_r$ $Đ'$ $P'_{o.c}$	10.7 1.5 0.6	7.40 0.74 0
3	1	I = 250 A U = 30 V	$Đ_r$ $Đ'$ $P'_{o.c}$	8.05 1.13 0.60	5.60 0.56 0
4	1	I = 160 A U = 26.4 V	$Đ_r$ $Đ'$ $P'_{o.c}$	4.53 0.63 0.60	3.13 0.31 0
5	4	–	$Đ_r$ $Đ_{0r} = Đ' + P'_{o.c}$ $Đ_{0r} = Đ_r + Đ' + P'_{o.c}$ $Đ_{str}$	44.75 8.66 53.41 85.88	30.94 (7.735) 3.10 (0.775) 31.52 (7.850) 24.7

Table 9. Comparative costs and power losses in a four-station system

Power source	$\frac{P_b - P_r}{P_b}\cdot 100$ %	$\frac{P' + P'_{o.c}}{P}\cdot 100$ %	$\frac{P_{ol.b} - P_r}{P_{ol.r}}\cdot 100$ %
TDM-503	–	16.6	–
TDEM-501	41	9.8	64
Note. P_b — basic power.			

transformer to be Q_{n1} / Q_b = 1 (where Q_n is the weight of the new multi-station system; Q_b is that of the basic variant). The second system is made up by TDF-1601 transformers (2 pcs) and 12 welding current regulators OI-1225UKhLZ, each of which consists of four chokes (48 welding stations altogether). The relative weights of this variant Q_{n2} / Q_b = 0.6. i.e. by 40 % less than in the basic one. The third system consists of TDEM-1201 transformers (3 pcs) and 48 welding current regulators (48 welding stations all in all). Relative weight is Q_{n3} / Q_b = 0.59, i.e. the total weight of this system is by 41 % smaller than in the basic variant. The fourth system is made up of one TDEM-3001 transformer and 48 welding current regulators. Relative weight is Q_{n4} / Q_b = 0.58, i.e. the total weight of this system is by 42 % smaller than in the basic variant. The fifth system is made up of one transformer TDEM-501 and four welding current regulators. Relative weight is Q_{n5} / Q_b = 0.66, i.e. the total weight of this system is by 34 % smaller than in the basic variant. In the third–fifth variants the principle of welding mode regulation is the same as that of the thyristor-controlled welding transformer (see item 3 of this work) of TDT type — each station consists of two chokes and thyristor regulator. Thus, each of the proposed multi-station systems for 48 stations consumes approximately 40 % and that with four stations — 34 % less of the deficit electrical engineering materials than in the basic variant.

In terms of power saving let us compare first the four-station TDEM-501 system with four TDM-503 transformers (basic variant). Table 8 gives four variants of the mode of welding station operation (see items 1–4) with the same demand factor β = 0.6. These modes correspond to certain values of power P_m consumed from the mains, as well as power losses in welding P' and $P'_{o.c}$. Item 5 gives all the consumed powers and power losses in the systems in the four stations.

Table 9 shows the fraction of overall losses in total power consumed by the system when using the rated power of all the four stations. Most of this power is lost in the basic variant (16.6 %). Four-station system based on TDEM-501 loses just 9.8 % and draws by 41 % less power from the mains, whereas the relative losses are by 64 % smaller than in a system consisting of four TDM-503 transformers.

Table 10 gives four variants of welding station operation: (items 1–4) multi-station systems (48 stations) based on transformers of different types: basic variant TDM-503 (48 pcs), as well as TDF-1601 (2 pcs), TDEM-1201 (3 pcs) and TDEM-3001 (1 pcs) with different demand factors β. These modes correspond to different power values both those drawn from the mains P_m and lost in welding P' and in open-circuit mode $P'_{o.c}$. Item 5 gives the total consumed and lost power for 48 stations.

Table 11 gives the share of overall losses of the system in the total power drawn by it from the mains at rated power consumption by 48 stations. Most of

Table 10. Operating modes of multi-station systems (48 stations)

Technology variant No.	Number of stations n, pcs	Station operating mode	Power	Transformer power and losses, kW			
				TDM-503	TDF-1601	TDEM-1201	TDEM-3001
1	8	β = 0.45 I = 500 A U = 40 V	Đ$_r$ Đ′ $P'_{o.c}$	129 18.0 6.6	91 11.0 0	85 6.8 0	85 6.8 0
2	16	β = 0.50 I = 250 A U = 30 V	Đ$_r$ Đ′ $P'_{o.c}$	107 15 12	76 9.1 0	71 5.7 0	71 5.7 0
3	16	β = 0.75 I = 200 A U = 28 V	Đ$_r$ Đ′ $P'_{o.c}$	120 16.8 6	85 10.2 0	79 6.3 0	79 6.3 0
4	8	β = 0.40 I = 150 A U = 26 V	Đ$_r$ Đ′ $P'_{o.c}$	22 3.0 7.2	16 1.9 0	14 1.12 0	14 1.12 0
5	48	–	Đ$_r$ Đ$_{0r}$ = Đ′ + $P'_{o.c}$ Đ$_{0r}$ = Đ$_r$ + + Đ′ + $P'_{o.c}$ Đ$_{str}$	378 85 463 1031	268 (5.58) 32 (0.67) 300 (6.25) 283	249 (5.19) 20 (0.42) 269 (5.60) 255	249 (5.19) 20 (0.42) 269 (5.60) 248

Note. Power drawn from the mains $P_m = P_r + P' + P_{o.c}$, from which $P_m = (UI\beta) / (\eta \cos \varphi)$ — power consumed for rated load, $P' = P_m (1 - \eta)$ — power losses in welding, $P'_{o.c} = P_{o.c}n(1 - \beta)$ — power losses in open-circuit mode; $P_{t.l}$ — total losses; $P_{str} = P_rN$ — claimed power.

the power (18.4 %) is lost in the basic variant. In multi-station systems based on TDEM, the fraction of overall losses is equal to 7.4 %, they draw by 42 % less energy from the mains, and the relative losses of one station in the system are by 76 % less than those of the basic source.

Tables 8 (system of four stations) and 10 (system of 48 stations) also give the power drawn from the mains P_m and total power losses $P_{t.l}$ per one welding station (see the value in parenthesis in Tables 7, 8 and 10). Comparison of the data in these Tables shows that the greater the number of stations for which the system is designed, the higher is its power efficiency. Power consumed by one station of the four-station system compared to the basic variant decreases by 41 %, and its losses –– by 64 %; in the case of a multi-station system consisting of 48 stations, these values are equal to 45 and 76 %, respectively. As is seen from Table 7, the area taken up by one welding station of the four-station system (values in parenthesis), is reduced more than 3 times, and in the 48 station system –– from 3.6 to 6.3 times.

Thus, use of multi-station power systems leads to saving of electrical engineering materials in their fabrication by 33–40 %, and of power in operation –– by 35–40 %. They take up 3–6 times less production areas and the cost of depreciation, maintenance and repair is reduced 2–3 times.

It is rational to mount multi-station systems in major enterprises for metal structure fabrication, in the shops with a large number of welding stations. Conducted tentative calculations showed than the cost of development of multi-station systems will be returned for the customer in 1–2 years.

It should be noted that at calculation of the cost-effectiveness of multi-station system application, other positive factors should be also taken into account, for instance, possibility of mounting PDAS in each welding station makes such a station versatile: it is possible to perform welding with electrodes both at direct and alternating current, as well as nonconsumable electrode welding of stainless steels, aluminium and its alloys. In addition, PDAS facilitates welder's labour, improves welding quality, and increases the fraction of arcing time in the total welding time.

Table 11. Comparative losses and power losses in the system of 48 stations

Power source	$\frac{P_b - P_r}{P_b} \cdot 100$ %	$\frac{P' + P'_{o.c}}{P} \cdot 100$ %	$\frac{P_{t.l.r} - P_{t.l.r}}{P_{t.l.r}} \cdot 100$ %
TDM-503	–	18.4	--
TDEM-501	35	10.7	62
TDF-1601	42	7.4	76
TDEM-3001	42	7.4	76

CONCLUSIONS

1. Application of PDAS developed at PWI in welding transformers allows lowering open-circuit voltage of the transformer, thus saving power by 30–40 %, and decreasing the consumption of electrical engineering materials by 30 %.

2. System of multi-station power supply, which consists of a powerful transformer with a flat external characteristic, powering the station equipment, consisting of an adjustable choke and PDAS, provides a 2–4 times power saving (depending on the quantity of welding stations) compared to a multi-station DC system, while requiring 2–10 times less production areas for system mounting and providing a 2–3 times reduction of the cost of depreciation, maintenance and repair of equipment.

1. Zaruba, I.I., Dymenko, V.V., Bolotko, V.I. (1989) Welding transformers with arcing stabilization devices. *Avtomatich. Svarka*, **10**, 46–51.
2. Pentegov, I.V., Dymenko, V.V., Rymar, S.V. (1995) Influence of saturation of welding transformer magnetic system on AC arcing stability. *Ibid.*, **7**, 35--40.
3. *GOST 25616–83*: Arc welding power sources. Methods of testing the welding properties. Introd. from 01.01.84 to 01.01.89.
4. Zaruba, I.I., Dymenko, V.V., Bolotko, V.I. (1982) Application of arcing stabilizers to decrease the open-circuit voltage of manual arc welding transformers. *Avtomatich. Svarka*, **10**, 27–31.
5. Zaruba, I.I., Dymenko, V.V. Kukharsky, V.Ya. (1991) Application of multi-station AC power sources for arc welding. *Ibid.*, **2**, 59--63.

EXTENSION OF SERVICE LIFE OF COLUMN EQUIPMENT AT OIL REFINERIES*

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Considered are the peculiarities of application of the technology for repair of durable oil refinery large-size column equipment made from two-layer steel St.3sp + 08Kh13, which is operated at a temperature of up to 300--400 °C.

Keywords: *column, two-layer steels, cracks, hardness, corrosion, examination of columns, defects, grooving of defects, welding, cladding, tests, extension of service life*

Two-layer steels of the St.3sp (killed), 09G2S, 16GS, 20K and 17GS grades with a cladding layer of steel 08Kh13 are widely used for the manufacture of casings of columns, tanks and other equipment used at oil refineries [1–7].

Casings of columns and some tanks used at oil refineries, comprising a cylindrical part, upper and lower bottoms, branch pipes and manholes, made from the above two-layer steels, are operated mainly at temperatures of up to 360–400 °C and under a low pressure of up to 0.2–0.5 MPa, or in low vacuum of 20–60 mm Hg.

Oil refinery column equipment used for refining of low-sulphur grades of oil and made from the above steel grades has been in operation in Ukraine since 1960, involving no problems in terms of repair. The situation changed in refining of oil with increased and high content of hydrogen sulphide H_2S. The presence of the latter in a product refined raises the degree and rate of degradation of steel, both carbon and stainless high-alloy steels experiencing degradation [8--10].

Typical defects, which may be formed in casings of columns and tanks under certain conditions during a long-time operation in oil refining, include corrosion hydrogen sulphide cracking of welds and corrosion-resistant layer of steel 08Kh13, pitting corrosion of the cladding layer, and increased hardness of the cladding and base layers of two-layer steel [8, 9]. General corrosion of the cladding layer is insignificant. Thus, in column K-2 of steel 16GS + 08Kh13, 16 mm thick, which was in operation at a temperature of 360 → → 100 °C (bottom and top of the column, respectively) for 38 years, thickness of the corrosion-resistant layer of steel 08Kh13 decreased by 0.2–0.5 mm (0.005–0.013 mm / year). Pitting corrosion of casings of the above steels has the form, mainly, of fine pits up to 0.5--1.0 mm in diameter and 0.2–0.5 mm deep.

If the prescribed welding technology is not kept to, such welding defects as undercuts, lacks of fusion, pores or rolls may be formed in casings of the column equipment, and in the cases of using stable austenitic welding consumables the typical defects include solidification cracks in welds and repair claddings. Structural changes take place in the base and cladding layers of steel during a long-time operation of column equipment. Data of Table 1 and metallographic examinations, by an example of steel 16GS + 08Kh13 cut from oil refining column K-2 after 38 years of operation, evidence a considerable diffusion of carbon from steel 16GS into the corrosion-resistant layer. In this case, a carbon-depleted interlayer is formed in the joining zone of layers in steel 16GS, while in the boundary region in steel 08Kh13 the concentration of carbon increases. The zonal increase of carbon in steel 08Kh13 leads to coagulation of carbides along the grain boundaries, formation of martensite, and increase of hardness of the cladding layer. Hardness of the cladding layer in some regions of the casing of this column grew to *HB* 304–320. The similar situation was observed also in examination of specimens of two-layer steel St.3sp + 08Kh13, 30 and 10 mm thick, cut from column K-5 of the primary oil refining unit AVT, and K-5 for cleaning of oil from sulphur, after 38 years of operation. The joining zone of layers in initial steel 09G2S + 08Kh13 made by the electroslag cladding method is almost 2 times as wide as that in steel made by the pack method.

No increase of sulphur content in metal of column casings, welds and claddings occurs in refining of hydrogen sulphide containing oil. Nor does the content of manganese sulphides susceptible to expansion in contact with hydrogen grow during operation.

According to the regulations for column equipment in force in the oil refining industry [5–7], it is recommended to limit hardness of the cladding layer of

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Table 1. Chemical composition of metal in the joining zone of layers in two-layer steel 16GS + 08Kh13 after 38 years of operation of oil refining column at temperatures of 360 → 100 °Ñ

Examination object	Chemical composition, wt.%				
	Si	Cr	Mn	Fe	C
Decarburised zone in base layer of 16GS	0.766	0.078	1.146	98.034	0.002
Carburised zone in corrosion-resistant layer of 08Kh13	0.485	11.928	0.468	86.364	0.755
Corrosion-resistant layer 08Kh13	0.461	12.118	0.421	86.962	0.039

steel 08Kh13 to a value of *HB* 220. Such requirements to hardness are specified for initial steel subjected to heat treatment [1], and for new equipment made from this steel. During operation, hardness of the cladding layer of 08Kh13 increases to more than *HB* 220 [6--9] (in the critical cases, to *HB* 400–600), which is attributed to formation of martensite. Steel 08Kh13 is metastable in structure (ferritic and ferritic-martensitic) and, therefore, in properties, depending upon the content of chromium and carbon, as well as the proportion of these elements [11]. Increase in hardness of both layers of two-layer steels and cracking may result from their saturation with hydrogen during operation [9, 10, 12–14].

Comparative analysis of the corrosion condition of columns K-2, K-5, K-6, K-12 / 1 and K-12 / 2, and column-type tank E-23 of unit AVT at Joint Stock Company «Ukrtatnafta» covering the last 6 years, as well as columns K-5 for cleaning of oil from sulphur, and primary oil refining column K-2, which were removed from operation after 38 years of being in service, shows that the above defects in casings are not of a mass character. They are formed mostly in the welds and heat-affected zone (HAZ) of some welded joints and repair claddings. Thus, cracks in HAZ in five locations of the welded joints and a crack in the weld of one branch pipe were formed in column K-2 of the AVT unit during the last two years (scheduled outages and repairs are performed every two years), hardness of the cladding layer of 08Kh13 being *HB* 250. And in column K-5 at hardness of claddings on the welds equal to *HB* 380, the cracks were formed in eight circumferential, vertical and meridian welds (area of the internal surface of the said column being 507 and 700 m^2). In regions 15–650 mm long, the length of the cracks in column K-2 was 3–15 mm, their depth was down to 5 mm, and spacing between the cracks was 5--15 mm, while in column K-5 the length of the cracks was 140–400 mm, and they were 6 mm deep.

No cracks were revealed in welds and cladding layers in columns K-6 at hardness of some regions of the cladding layers and claddings on the welds equal to *HB* 250--300, in columns K-12 / 1 at hardness of *HB* 177–391, in columns K-12 / 2 at hardness of *HB* 180–363, and in tank E-23 at hardness of *HB* 167–366. Increase in hardness of the cladding layer to more than *HB* 220 may lead to cracking in casings of the columns, but is it not the unambiguously established criterion of a reject indicator for all types of oil refinery column equipment, as it is specified in regulatory documents [5--7].

Metal of the base (load-carrying) layer of casings of the columns degrades to a lesser degree than that of the cladding layer of 08Kh13. Hardness of the base layer of steels St.3sp, 09G2S and 16GS grows insignificantly during the long-time operation, and, as shown by analysis covering the last six years, except for rare cases (2005, column K-12 / 1 at points 30 and 31 — *HB* 286 and 225), it is not in excess of a rated level of *HB* 190. Mechanical properties of the load-carrying layer used to evaluate strength of the column casings remain sufficiently high (Table 2).

Performance of casings of the columns depends upon many factors, and strongly upon the thoroughness of examination of the corrosion condition of equipment and the high skill of repair operations. An important link of the extension of life of oil refinery column equipment is the development of technologies for repair of welded joints and a cladding layer by welding and deposition methods.

Welding repair of defects in the base layer of the columns was performed with UONII-13 / 45 electrodes of the E-42A type under conditions and using parameters specified in regulatory documents in force in the industry [3–7]. Given that no requirements for intercrystalline corrosion resistance are imposed on the corrosion-resistant layer of 08Kh13 in the said columns, and that the service temperatures of the columns are not higher than 360 °C, the composition of metal of the Kh25N13 type, i.e. ANV-70B electrodes of the E-10Kh25N13G2 type [14] and welding wire of the Sv-07Kh25N13 grade, was chosen for repair of the 08Kh13 layer and cladding of the low-carbon welds. Wire cladding was performed using a semi-automatic device in argon atmosphere with an addition of oxygen. Electrodes ANV-70B developed by the E.O. Paton Electric Welding Institute, with coverings made from domestic raw materials, are manufactured by State Company «E.O. Paton Electric Welding Institute Pilot Plant for Welding Consumables». Welding with the ANV-70B electrodes provides the stable arc, easy re-ignition of the arc, good detachability of the slag crust, and uniform formation of the welds and claddings in all spatial positions. Chemical composition and mechanical properties of metal deposited with the ANV-70B electrodes meet requirements of GOST 10052–75, and content of the ferrite phase in the deposited metal is within 6–10 %.

Rigid specimens of steels 16GS + 08Kh13 and St.3sp + 08Kh13, 10, 16 and 30 mm thick, with a level of hardness of the cladding layer equal to *HB* 250--380, cut from the columns after 38 years of op-

Table 2. Mechanical properties of two-layer steel St.3 + 08Kh13 and 16GS + 08Kh13 specimens cut from column casings after 38 years of operation

Steel grade	Type and size of cross section of specimens	σ_t, MPa	$\sigma_{0.2}$, MPa	δ, %	$KCU_{+20\ °C}$, J / cm^2	
					Base (load-carrying) layer	Cladding layer of 08Kh13
Steel St.3sp + 08Kh13, 30 mm thick, AVT unit column K-5						
St.3sp (GOST 380--60)	Cylindrical (GOST 1497–84), 5.8 mm diameter	423.5 423.7 425.7	219.5 189.2 215.4	52 51 56	166.3 243.8 257.5	–
08Kh13 (EI496)	Flat (GOST 1497--84), 4.5 mm thick	1052.7 1055.8	881.7 881.4	10.9 10.4	–	101.4 94.3
Requirements of GOST 380–60 to plate steel St.3sp, not less than 26–40 mm thick		380 490	240	25	50	–
Steel 16GS + 08Kh13, 16 mm thick, column K-2 removed from operation						
16GS	Flat (GOST 1497--84) without removal of cladding layer, 16 × 18 mm	556.0 572.0 555.9	373.3 417.5 369.5	12.4 15.0 11.8	150.1 144.2 158.9	–
Requirements of GOST 19282–73 to plate steel 16GS, 10–20 mm thick		480	315	21	59	–

eration, and having the form of «boats» (Figure 1), butt joints (Figure 2) and O.I. Steklov 130 mm diameter test samples with a 40 mm diameter circumferential weld, were welded to develop the repair technology (Table 3). To compare, specimens of steel 09G2S + 08Kh13, 10 and 20 mm thick, in the as-received state (not being in operation) were welded and clad. Rigidity of the specimens was provided by welding them on the contour to thick plates. The cladding layer was deposited with the ANV-70B electrodes and Sv-07Kh25N13 wire in the flat and other spatial positions applicable to repair of column casings. Cladding of the boat-type specimens simulated the cases of repair of the cladding layer of the columns, and butt welding simulated repair of probable cracks in the weld and cladding layer (with transition to the carbon weld or base layer). Cladding with the ANV-70B electrodes was performed in two layers, and that with the Sv-07Kh23N13 wire — in three layers, by keeping to the standard rules of welding two-layer steels (Figures 1, 2). Dilution of the deposited metal with the carbon one should be no more than 30 %. This provides a stable austenitic-ferritic structure of the transition zone metal and a high guarantee of the absence of solidification cracks. The specified technology being kept to, hardness of the metal deposited with electrodes ANV-70B (Figure 3) and wire Sv-07Kh25N13 is within 1500–2000 MPa (*HB* 150–200), which is lower than hardness of the corrosion-resistant layer of 08Kh13 of the columns being in operation. Despite a high rigidity of the welded specimens of steels 16GS + 08Kh13 and St.3sp + 08Kh13 after a long-time operation, having an increased level of hardness equal to *HB* 250–380, no cracks were detected in the metal deposited with electrodes ANV-70B and wire Sv-07Kh25N13 without preheating.

Given that hardness of the cladding layer of the columns repaired is higher than a rated value of *HB* 220, the presence of martensite in the 08Kh13 layer, increased rigidity of a number of components of the columns, the necessity of preheating and heat treatment of weld edges of the deposition zone (Tables 3 and 4) in the course of repair was verified.

At the presence of martensite in the cladding layer (in cases under consideration its content of the 08Kh13

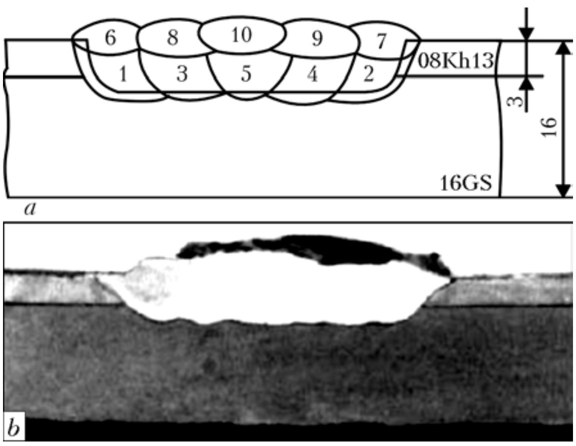

Figure 1. Cladding layer of 08Kh13 on steel 16GS + 08Kh13: *a* — shape of defect grooving and sequence of ANV-70B electrode deposition of transition (1--5) and cladding (6--10) layers; *b* — macrostructure of metal deposited in vertical position

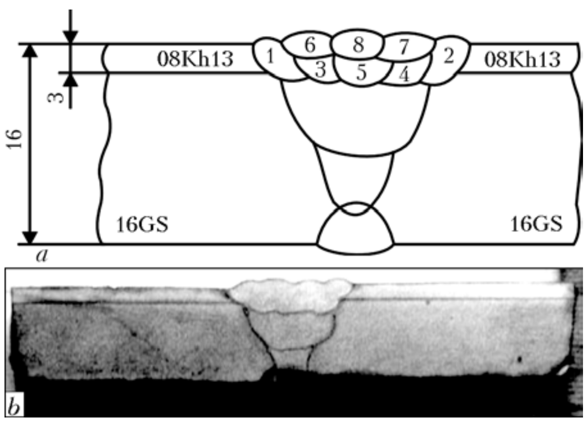

Figure 2. Weld with a crack on the side of the cladding layer of steel 16GS + 08Kh13: *a* — shape of defect grooving in the crack zone and sequence of ANV-70B electrode deposition of beads of transition (1–5) and cladding (6--8) layers; *b* — macrostructure of metal of the repaired weld in cross section

Table 3. Properties of welded joints of two-layer steels 16GS + 08Kh13, 16 mm thick, steels 09G2S + 08Kh13, 20 and 10 mm thick, and steels St.3sp + 08Kh13, 10 mm thick

Method for cladding corrosion-resistant layer on low-carbon welds	Grade and diameter of electrodes, cladding wire	Grade of steel welded, welding conditions	Steel layer	Hardness *HB*			
				Steel before welding	HAZ, steel 08Kh13 (3–4 mm from fusion line)	Metal	
						Low-carbon weld*	Cladding on weld
Manual arc welding with covered electrodes	3 mm diameter electrodes ANV-70B	16GS + 08Kh13 after operation in oil refining	Base 16GS	131	--	179	--
			Cladding 08Kh13	311	302	--	197
	Same	Butt welding with preheating to 350 °C	16GS	143	--	153	--
			08Kh13	302	321	—	197
		16GS + 08Kh13 after operation and heat treatment (640 °C for 1 h, air)	16GS	137	--	--	--
			08Kh13	227; 204	197; 223	241	197
Semi-automatic arc welding	1.2 mm diameter wire Sv-07Kh25N13	16GS + 08Kh13 after operation in oil refining	16GS	121	--	170	--
			08Kh13	307	307	--	192
Manual arc welding with covered electrodes	3 mm diameter electrodes ANV-70B	09G2S + 08Kh13, 20 mm thick, before operation	09G2S	179	--	179	--
			08Kh13	179	197	--	197
		09G2S + 08Kh13, 10 mm thick, before operation	09G2S	156	--	187	--
			08Kh13	170	179	--	187
		St.3sp + 08Kh13 after operation	St3sp	167	--	182	--
			08Kh13	270	--	--	180

*Base layer was welded with electrodes UONII-13.45. HAZ metal of 08Kh13 layer contains no cracks.

layer amounted to 40 %), it is recommended to perform cladding with preheating to 300–350 °C. In this case, width of the transition zone (carbon steel 16GS, St.3sp and 09G2S – 08Kh13 layer) does not increase, no structural changes occur, and the probability of cracking of the 08Kh13 layer decreases.

Heat treatment for steels under consideration, if necessary (e.g. hardness of the cladding layer is too high, or cracks are formed in the 08Kh13 layer cladding), should be performed at temperatures of 640–700 °C for not less than 1 h. In this case, hardness of the repaired zones of the joints decreases to a rated level (below *HB* 220) (Tables 3 and 4).

To illustrate, Table 5 gives mechanical properties of a welded joint in steel 16GS + 08Kh13 after 38 years of operation, which was made by the developed technology. Deposition of the cladding layer of the weld was made with electrodes ANV-70B. The developed technology is recommended for application at Joint Stock Company «Ukrtatnafta» to repair casings of the columns of steels St.3sp + 08Kh13 and 16GS + 08Kh13.

In 2005, «Ukrtatnafta» repaired the casings of columns K-2, K-6 and, partially, K-5 of steel St.3sp + + 08Kh13, 16, 20, 24 and 30 mm thick, with an increased hardness of the cladding layer of 08Kh13 to *HB* 250, 250–300 and 160–380, respectively, using the recommended technology and electrodes ANV-70B. Before repair, the casings of the columns were examined to detect defects (cracks in welds and HAZ, welding defects, zones with corrosion damage, etc.).

Table 4. Effect of restoration heat treatment on hardness of the 08Kh13 cladding layer of two-layer steel 16GS + 08Kh13 after 38 years of operation

Restoration heat treatment conditions*		Hardness of steel 08Kh13, *HB*
Ò, ¹Ñ	Holding time, h	
Without heat treatment		285, 277
250	1.0	277, 277
300	1.0	277, 277
350	1.0	285, 285
400	1.0	268, 265
580	1.0	277, 269
640	0.5	255, 255
640	1.0	197, 197
700	1.0	197, 197
730	1.0	187, 179
850	1.0	179, 179

*Cooling of specimens after heat treatment was performed in air

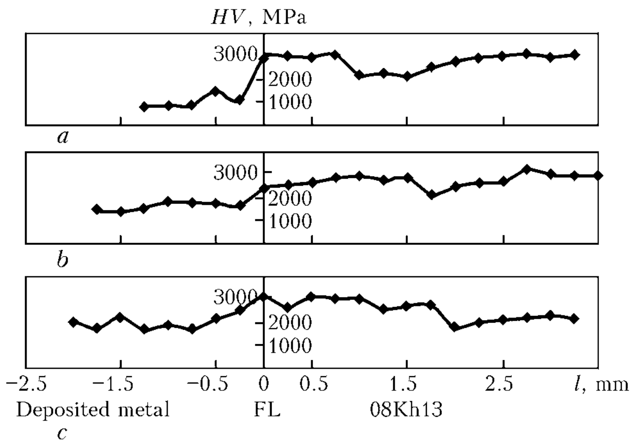

Figure 3. Distribution of microhardness in a repair cladding made with electrodes ANV-70B for steel 16GS + 08Kh13 (*a*), with preheating and concurrent heating of the repaired zone to 350 °C (*b*), with heat treatment of the repaired zone prior to cladding under conditions of 640 °C for 1 h, air (*c*)

Table 5. Short-time mechanical properties of welded joints in two-layer steel 16GS + 08Kh13, 16 mm thick, cut from column K-2

Specimen No.	Filler materials for welding		Mechanical properties					
	Base layer of 16GS (hardness of steel 16GS)	Transition and cladding layers	$\sigma_{0.2}$, MPa	σ_t, MPa	δ, %	Fracture location in specimen	*KCU*, J / cm^2	
							Carbon weld	Steel 16GS
A34	UONII 13 / 45 (weld root) + UONII 13 / 55 (*HB* 131)	Electrodes ANV-70B	432.3 425.4	524.5 546.7	13.0 12.0	Base layer of 16GS	220.7 232.5 225.6	150.1 144.2 158.9
A33	UONII 13 / 45 (weld root) + UONII 13 / 55 (*HB* 121)	Wire Sv-07Kh25N13	420.5 404.4	520.8 520.7	16.3 17.5	Same	229.5 252.2 225.6	149.2 150.4 154.8
Steel 16GS	Requirements of GOST 19282–73 to 16GS steel plate 10–20 mm thick (not less than)	–	315.0	480.0	21.0	–	--	59.0

Main defects detected in the casing of column K-2 were cracks in HAZ of the welds and one crack in the weld of a clad branch pipe, those in K-5 were cracks in the welds, and those in K-6 were welding defects (pores and undercuts). Grinding out of defects in the weld cladding layer damaged with cracks was made by the abrasive method. Removal of cracks was inspected by the visual-optical and liquid penetrant methods. Considering the degree and character of corrosion damage, repair of the casings was carried out without removal of inner equipment (disks, etc.). Based on the accessibility conditions, deposition of the corrosion-resistant layer was performed only with electrodes. In columns K-2, K-6 and K-5, repair of the cladding layer was carried out using electrodes ANV-70B.

No cracks in claddings made with electrodes ANV-70B and HAZ of the claddings on the 08Kh13 layer were detected by the visual-optical inspection method. Therefore, all repair claddings in columns K-2, K-5 and K-6 were performed without preheating of the zones repaired. Heat treatment of the locations repaired prior to welding and cladding was not necessary at this stage of repair of the column casings. After repair, the column casings were subjected to visual-optical inspection and pressure tests. No defects were revealed in the column casings, except for column K-5. A crack up to 550 mm long was formed in the HAZ metal of one of the meridian welds on a transition piece between cylindrical shells of the column, 8000 and 5500 mm in diameter, welded of lobes of steel St.3sp + 08Kh13, 30 mm thick. The probable cause of its formation was a high level of welding stresses in a region 3--5 mm wide between the repaired weld and weld for joining a bracket to fix the inner devices of the column (disks, etc.). A defective location was repaired, and the column was again subjected to inspection to detect defects, and to pressure tests. No defects were revealed in the casing.

Based on the results of corrosion examination of columns prior to repair, degree and character of corrosion damage of casings, relatively low level of hardness of the cladding layer of the examined zones (up to *HB* 250–380), and results of quality control of the repaired joints [15–17], the life of the columns was extended to another 2 years. The equipment will be subjected to the scheduled regular examination of its corrosion condition.

CONCLUSIONS

1. The baseline technology was developed for repair of the oil refinery column casings made from two-layer steels St.3sp + 08Kh13 and 16GS + 08Kh13 with an increased hardness of the corrosion-resistant layer, which are operated at temperatures of up to 300–400 °C.

2. The oil refinery column casings of steel St.3sp + + 08Kh13 with an increased hardness of the corrosion-resistant layer, operated at temperatures of up to 360 °C, were repaired.

1. Golovanenko, S.A., Meandrov, L.V. (1966) *Manufacturing of bimetals*. Moscow: Metallurgiya.
2. (1981) *Corrosion*: Refer. Book. Ed. by L.L. Shrayer. Moscow: Metallurgiya.
3. Tomashov, N.D., Chernova, G.P. (1986) *Theory of corrosion and corrosion-resistant structural alloys*. Moscow: Metallurgiya.
4. *GSTU 3-17-191–2000*: Steel welded vessels and apparatuses. General specifications. Introd. 16.02.2000.
5. *GSTU 3-020–2001*: Fusion welding of metallic materials in chemical and oil engineering.
6. *OTU 3–01*: Vessels and apparatuses. General specifications on repair of casings. Volgograd: VNIKTI Neftekhimoborudovaniya.
7. *RUA--93*: Guidelines on service and repair of vessels and apparatuses operating under pressure of up to 0.7 MPa and in vacuum. Volgograd: VNIKTI Neftekhimoborudovaniya.
8. *ITN–93*: Instructions on technical supervision and procedure of inspection of equipment for oil-refining and petrochemical productions. Volgograd: VNIKTI Neftekhimoborudovaniya.
9. Vasylenko, I.I., Shulte, O.Yu., Radkevich, O.I. (1990) Influence of chemical composition and technology used to make steels on their sensitivity to hydrogen cracking and hydrogen sulphide corrosion cracking. Review of foreign researches. *Fizyko-Khim. Mekhanika Materialiv*, 6(**4**), 8–22.
10. Pressouyre, G.L., Blondeau, R., Cadiou, L. (1984) HSLA steels with improved hydrogen sulphide cracking resistance. In: *Proc. of ASM Conf.* (Philadelphia, 1984).
11. Gulyaev, A.P. (1977) *Metals science*. Moscow: Metallurgiya.
12. Archakov, Yu.I. (1985) *Hydrogen corrosion of steels*. Moscow: Metallurgiya.
13. Pokhmursky, V.T., Melekhov, R.K., Krutsan, G.M. et al. (1995) *Corrosion-mechanical fracture of welded structures*. Kyiv: Naukova Dumka.
14. Rubenchik, Yu.I., Sokolov, R.P., Malyshev, Zh.N. et al. (1988) Effect of non-metallic inclusions on hydrogen-induced delamination of low-alloy steels. *Fiziko-Khim. Mekhanika Materialov*, 24(**3**), 47–51.
15. *TU U 28.7-5416923-074–2005*: ANV-17u, ANV-70B, ANV-70R, ANV-71 metal covered electrodes for manual arc welding.
16. *DSTU 4046–2001*: Technical diagnostics. General specifications. Introd. 27.01.2001.
17. *DNAOP 1.3.00-8.02–93*: Operations on assessment of residual performance of technological equipment for oil-refining, petrochemical and chemical productions. Kiev.

EXTERNAL ELECTROMAGNETIC EFFECTS IN THE PROCESSES OF ARC WELDING AND SURFACING (REVIEW)

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Classification of controlling magnetic fields used for implementation of electromagnetic effects is given. Published data on the efficiency of application of different electromagnetic effects in arc welding and surfacing processes are systematized and generalized. It is established that the spectrum of addressed technological problems is related to vector, amplitude and frequency characteristics of the controlling magnetic fields. The most promising ways of improving these technologies are identified.

Keywords: arc welding and surfacing, electromagnetic effects, controlling magnetic fields, solidification, formation and parameters of quality of welds

By now a significant amount of works considering peculiarities of application of various external electromagnetic effects (EME) in processes of arc welding and surfacing were published. Basically these are used in the cases when for provision of the required quality of welds, traditional technical and technological methods are insufficient. Our analysis of publications has shown that the spectrum of problems solved by means of EME is wide enough, however there are no generalizing data allowing in each specific case peak efficiency to be obtained from the usage of given effects. This work attempts systematization and generalization of the data on application of various EME and definition on this basis of promising ways of their perfecting.

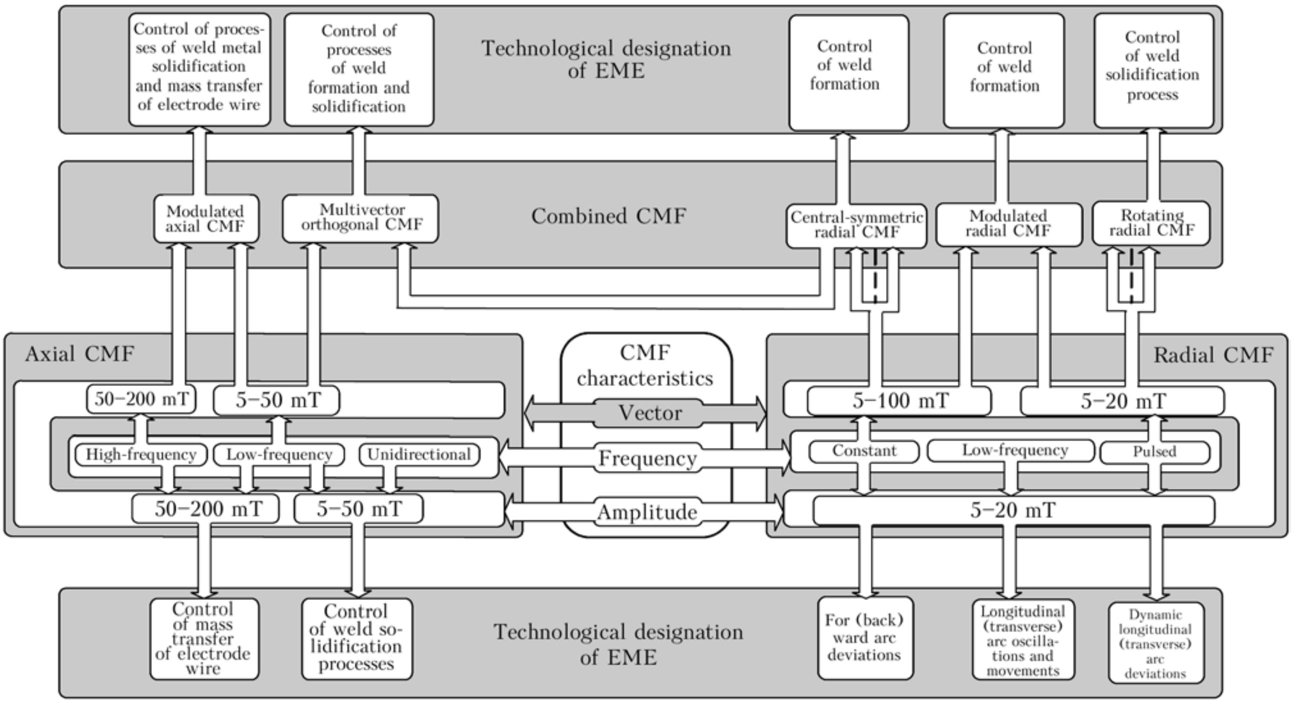
Analysis of publications in this field has allowed singling out basic attributes qualitatively distinguishing the applied EME. The basic one being the sense of the vector of the controlling magnetic field (CMF) in relation to the object of effect. By this attribute CMF are subdivided into the axial (longitudinal) and radial (transverse) ones. With the former ones the vector of induction is parallel; with the latter it is normal to the electrode axis. Additional, not less important distinctive attributes of the two specified groups of UMP, are their frequency and amplitude characteristics (Figure).

At analysis of axial CMF it was established that irrespective of the shape of pulses (sinusoidal or rectangular) they can conditionally be subdivided into unidirectional, low- (1--25 Hz) and high-frequency (from 200 Hz and above). Thus for low-frequency fields are most typical 5--50 mT ranges of inductions, while for high-frequency ones these are 50--200 mT. In the group of radial CMF in respect of frequency characteristics they are pulsed, low-frequency and constant. For all of them the range of inductions 5--20 mT is typical. CMF of the first group (with axial vector characteristics) are mainly applied in the cases when the object of effect is welding pool and mass transfer of the electrode metal, the second (radial) is the arc as a source of heating.

Characteristically, that in publications of recent years peculiarities of the use of combined EME is more often considered. Unlike traditional bipolar devices, at their implementation multipolar electromagnetic systems (EMS) are used, which structure includes *n* electromagnets with independent power supply systems. Depending on the combination of polarities of magnetizing currents, in their coils, in the zone of welding, are generated various in relation to the object of effect CMF. So, at alternating polarities of the magnetizing currents simultaneously passing through the poles of EMS, centrally-symmetrical radial CMF are generated in the zone of welding (see the Figure). Consecutive connection of opposite with respect to the axis of electrode pairs of poles with different polarities of magnetizing currents allows obtaining rotating radial magnetic fields. Simultaneous generation of different frequency CMF generates modulated axial and radial magnetic fields. Multivector orthogonal magnetic fields are obtained by consecutive generation in the zone of welding of axial low-frequency and radial centrally-symmetrical CMF.

The analysis has revealed that technological application of axial, radial or combined CMF is dependant on the choice of the object of effect. Thus the arc, welding pool or metal droplets on the butt end of the electrode can either be independent objects of EME, or, which is most typical, objects of simultaneous effect. In the latter case efficiency of EME is limited by the degree of positive action of the factors responsible for technological result in a chosen object of effect, or conversely, suppression of their negative effect in the others. We shall consider mechanisms of the effect and technological opportunities of the most commonly used methods of welding and surfacing using EME.

At generating in the zone of welding (surfacing) of low-frequency (10--30 Hz) axial CMF in the head, more heated, part of the pool are formed melt flows whose movement to its tail part occurs consecutively along each of the lateral fronts of solidification with



Classification of controlling magnetic fields

frequency of magnetic field polarity reversal. Accompanying it periodic changes of the temperature gradients near interphase of solidification front lead to respective alterations of the width of the zone of concentrational supercooling, which authors of [1–3] explain as the reason of achieving at given EME, effect of grain refining in original weld metal structure.

There are also other viewpoints on the mechanism of the effect of given EME on the processes of solidification. So, in [4, 5] in addition to the mechanism cited above, was also put forward an assumption of the existence of the effect of mechanical detachment of fragments of the produced crystallites with formation of additional centers of solidification. Authors of [6] explain grain refinement in the structure of welds by branching of the protruding portions of the solid phase during pulse growth. At welding commercially pure metals with small width of the two-phase zone, grain refinement of the structure is attributed to the changes of conditions of secondary boundaries formation [4]. However reported data sufficient for acknowledgement of the existence of the specified effects, as far as our information goes, are unavailable.

Efficiency of the effect of given EME on the processes of solidification depends on physical and chemical properties of materials to be welded. So, in welding alloys having a wide solidification temperature range, in the case of optimum CMF parameters, the effect of grain refinement was observed throughout the entire sections of welds [3, 7], while for those having narrow range, only near their longitudinal axis. This is explained by narrowness of the two-phase zone and poor development of the axes of second-order dendrites [5]. The effect of grain refinement was also detected in the near-weld zone, which is connected with increasing speed of HAZ metal cooling [7]. Solidification schemes are characterized by greater bending of crystallites in the process of their growing from the line of fusion to the center of welds. It ensures more favorable orientation of the junction of fronts of solidification in relation to tensile stresses [8].

Weld structure refining is accompanied by increased total length and reduced degree of orientation of grain boundaries and insignificant amount of intercrystalline precipitates [9, 10]. Thus absence of blockiness and smoothness of the geometry of elements of microstructure of the welds testifies to insignificant level of intragranular heterogeneity. This effect is explained by the increase and leveling of instantaneous speeds of solidification near the lines of fusion and axes of welds [11]. Reduction of chemical microheterogeneity, uniform distribution of alloying elements throughout the weld section to a greater degree is characteristic for welding of alloyed steels and alloys.

Positive changes in processes of solidification also explain reduction of the rate of overall corrosion of welds, increase of their stability against intercrystalline corrosion [12], improvement of mechanical properties [13, 14]. Improvement of plastic properties of welds and narrowing of brittleness temperature range occurring as a result of the rise in temperature of its lower boundary [15], is the reason of improvement of resistivity of welds to formation of hot cracks in welding members from aluminium [9, 3], magnesium [7], medium- and high-alloy steels and alloys [16].

Periodic migration of the melt from the head to the tail part of the pool contributes to increasing the area of their surface, leveling of the temperature in its peripheral and central areas, reduction in the variation of concentration of impurities and gases in the melt, stabilization of flat solidification front [3]. Reduction of superheating of the liquid phase before the solidification front assists in the reduction of thermal diffusion flow of hydrogen in the direction of fusion line. These factors contribute to the reduction of solubility of gases in the melt and create favorable conditions for detachment and easy emersion of pores on the surface of the pool. Owing to application of EME almost a 5 times reduction of porosity of welds in TIG welding of titanium and aluminium alloys [13, 17] and a 2.5 times in wet underwater welding of structural steels is noted [18].

Specificity of the arc behavior in axial CMF is its rotation around vertical axis with assuming a form close to conic, which promotes stabilization of its spatial position and allows adjusting its force effect on the pool melt practically without change of power [19]. Supervision of the arcing allowed assuming that active spot on the workpiece consists of separate more or less regularly located cathodic spots. It furthers intensification of the process of cathodic spraying of oxide films and reduction of the overall contents of oxide inclusions in the weld metal, which is especially inportant in welding of aluminium alloys.

Positive effect of axial CMF on the arc as a source of heating is used to advantage for improving the process of weld formation. EME on their basis are applied for provision of simultaneous melting of both edges of joints and stabilization of spatial position of the arc in TIG welding at forced modes and submerged arc welding of root welds of pipe joints [20]. With their help was achieved reduction of the quantity of passes without formation of undercuts in submerged arc TIG welding.

Application of comparatively high inductions of axial CMF (50–200 mT) leads to the increased depth of penetration of welds, which is explained by the reduction of cyclotron radius of the arc [21, 22]. However at control of hydrodynamics of the pool by means of EME, the increase in induction should be accompanied by the increase of the frequency of CMF. Considering lagging of the given effects, said range of inductions of the magnetic field can not ensure intensive movements of the pool melt and, as a consequence, control of the processes of solidification of welds. Such EME are basically applied for improving the processes of weld formation and mass transfer of the electrode metal.

Irreversible movements of the pool melt are achieved by generating in the zone of welding of unidirectional axial CMF. The arising centrifugal forces lead to splashing out of the melt at one and formation of an undercut at the other side of welds. Grain refinement in the original structure of the weld metal is observed at one, with respect to longitudinal axis, side of welds. Thus owing to asymmetry of the thermal field, displacement of the line of merger of crystallites was observed [9]. Therefore in downhand welding, EME on the basis of such CMF are inefficient, however they are usefully employed for depositing horizontal welds on vertical planes [23].

In MIG / MAG welding using axial CMF, centrifugal forces active inside droplets rotating with high speeds at the butt end of the electrode, change their shape from spherical to elliptic [8, 24, 25]. Thus there happens a reduction of thickness of liquid thermal insulating interlayer on the butt end of the electrode, therefore speed of melting of the electrode wire increases by 25–30 % at practically constant heat power of the arc [24]. However at inductions of CMF exceeding a threshold level (12–15 mT), frequency of droplets detachment from the butt end of the electrode decreases 2–3 times, stable spray transfer of the electrode metal is replaced by globular one. Growth of centrifugal forces inside the droplets leads to increased spatter and to perturbations of stability of the welding process [8].

The given circumstances prompt the expediency of application of axial CMF in MIG / MAG welding for making small thickness joints when EME on their basis improve processes of solidification and formation of welds and do not raise the level of spatter. It should be pointed out that most of the published works devoted to application of EME in consumable electrode welding are focused on the process of submerged arc welding [12, 19, 26, 27]. Their authors noted the effect of increasing the coefficient of transition into the weld of alloying elements, which is explained by the improvement of interaction of the electrode metal with walls of the slag bubble.

EME using high-frequency axial CMF are based on inducing either in the volume of the pool, or in the droplets of the electrode wire of eddy currents. At their interaction with radial component of CMF the volumetric axial force acting away from the electromagnet, is created. Its value is proportional to product $M(\partial M/\partial Z)$, where M is the mutual inductance of the object of control and the electromagnet in vertical direction. Such EME are used both for controlling of mass transfer of the electrode wire in arc brazing [28, 29], and for increasing current density in the tail part of the pool for raising efficiency of control of formation of welds in gravity welding. At their implementation temperature of droplets and workpiece surfaces remains practically unchanged, which excludes their superheating occurring, for example, in pulsed arc welding [29]. Especially important this can be for welding high-alloy steels and alloys, when burning out of fusible elements of the electrode wire takes place. Besides, in such welding losses due to spatter are practically excluded, and accuracy of dosage during application of coating is provided in surfacing. Thus there is an opportunity of controlling not only the process of droplet detachment from the butt end of the electrode, but also of formation of the trajectory of their movement in the required direction. This effect is used for improving the processes of overhead weld formation.

Common limitation of EME using axial high-frequency CMF and low-frequency with increased induction is the difficulty of their practical implementation. Maximal effect from their employment is achieved at high magnetization currents passing through coils of electromagnets. It causes necessity of their forced cooling and manufacturing from wound materials with significant cross-sections which worsens mass- and dimensions parameters of specialized torches and their handling. We shall notice that at use of high-frequency CMF, efficient EME are possible only at low inductance of coils of electromagnets, which requires optimization of their design data depending on specific welding conditions.

At EME using non-combined radial CMF (see the Figure), hydrodynamics of pool melt is controlled by deviations of oscillations or movements of the arc with frequency of the magnetic field in the direction normal to its lines of force, to the distance proportional to the amplitude value of its induction [30, 31]. At such manipulations with the arc deforming the surface of the pool with a force directly proportional to the square of the welding current, flows of melt in the direction, normal to magnetic flux of the CMF are formed.

At deviation of the arc with a constant CMF depth of lateral undercuts in the direction of solidification front increases, while in the direction of melting front it decreases [32]. Forward deviation of the arc leads to the increasing radius of the front of melting of the pool, which promotes reduction of the speed of movement of the central flow of the melt in the direction of its tail part, which explains the above effect. Thus horizontal component of the arc pressure keeps the melt at forward front of the pool, which ensures increase in thickness of the liquid layer under the arc, which, in its turn, increases capability of the pool to compensate casual deflections of the arc and heat flow pressure. In outcome the quantity of burns through [33] sharply decreases, the arc plume deflected towards the cold metal before the front of melting protects the surface of the joint from impurities and oxides [32, 33].

More efficient are EME based on application of alternating radial CMF for longitudinal and transverse oscillations of the arc. In the first case periodic changes of the speed of the melt flow in the direction of solidification front allow eliminating dendritic and forming equiaxed structure of welds [30]. However such positive changes occur not throughout the entire section of welds, but only in their central areas, which limits technological range of application of such EME.

Transversal oscillations of the arc (up to 9–12 mm) assist in stabilization of the process of arcing, elimination of overlaps on reinforcement, provide more uniform formation of back bead [30, 34]. Thus the shape factor of the welds increases 1.5–2.5 times at corresponding increase by 20–25 % of its width and reduction by 10–50 % of the depth of penetration [35]. This effect is augmented at increase in frequency of oscillations, which is explained by the reduction of pressure of the arc on the welding pool melt. Such changes of parameters of formation of welds promote grain refinement near the zone of fusion and reduction of shrinking and gas porosity, which improves mechanical properties of welded joints. Characteristic reduction of the degree of dilution of the filler metal by the parent, accompanied by almost two-fold reduction of hardness of welds, and improved filling the groove make it expedient to apply such EME for multipass welding and welding of two-ply steels. Besides, in surfacing, provision of uniform depth of penetration allows current values to be increased by 100–300 À, which causes both the increase of speed of melting of the electrode wire and efficiency of the given process.

In wide-layer surfacing, EME with radial CMF are applied for reciprocating movements of the arc on the butt end of the electrode strip. It allows stabilizing the arc process, reducing the lifetime of droplets at the butt end of the electrode and their average diameter. Thus the arc does not wander, but rather moves melting the electrode strip along its whole width, which promotes improvement of the deposited layer formation process and reduction of deformation of a workpiece [36, 37].

It is expedient to single out EME based on the use of combined CMF (see the Figure). Their essence consists in simultaneous or consecutive generation in the zone of welding of magnetic fields with different characteristics. So, combined constant and alternating transverse CMF are applied for controlling formation of welds in raised-speed welding of thin-walled cable sheaths [32]. Thus using constant CMF, the arc is deviated to the front of melting, which provides for reduction of the depth of undercuts, while alternating CMF are used to effect longitudinal oscillations of the arc for periodic «discharge» of superfluous volume of the melt from the front of melting to the front of solidification, which promotes increasing stability of the process of weld formation.

At superposition in the zone of welding using a quadrupole electromagnetic system of radial CMF such a resultant distribution of induction was reached at which it was equal to zero on the longitudinal axis of the arc and assumed its maximal values in the field of fronts of melting and solidification of the welding pool [38–40]. At certain amplitude and vector characteristics of CMF, such EME enabled without reduction in stability of arcing to achieve compensation of the gravitational forces deteriorating the process of weld formation in gravity welding.

Basic criteria for estimating efficiency of the processes of arc welding and surfacing with EME are the level of overall improvement of weld quality parameters, their universality (possibility to be applied under different types, methods and conditions of welding) and the possibility to be implemented by means of devices whose characteristics match the level of development of modern welding technologies and equipment.

Peak efficiency of EME is achieved provided CMF parameters match the preset conditions of welding or surfacing. The published works on optimization of EME are incomplete in that they used empirical dependences limiting the area of their application to investigated welding conditions [15, 41]. For predicting optimum parameters of CMF with consideration for specificity of thermal and physical properties of welded materials and modes of welding, definition of science-based criteria of optimization and creation on this basis of deterministic mathematical models is necessary. As of today such works were carried out successfully only for EME based on the use of low-frequency axial CMF [12, 42, 43]. However optimization of the parameters of CMF does not add to manufacturing capabilities of EME. Proceeding from the above, we consider that promising lines of include improvement of the existing and development of new technologies of welding and surfacing using CMF with parameters which have not been applied or were applied to a limited extent. For determining what these parameters should be, we shall analyze the factors restricting manufacturing capabilities of the known methods of welding and surfacing with EME.

At implementation of EME based on the use of axial low-frequency CMF, presence of even an insignificant magnetic field transverse component in the zone of arcing and melting of the electrode wire gives rise to negative by-effects. Under its effect the arc as the source of heating disperses, which leads to 20–30 % reduction of the depth of penetration, in most cases inadmissible [2, 13, 22]. In consumable electrode welding, its interaction with welding current in the droplet volume leads to deflection of trajectory of their movement, which can increase electrode wire metal spatter [8].

In order to completely to exclude the effect of CMF on the arc and the process of electrode wire metal transfer is practically impossible, it can only be diminished. Absence of transverse induction component of CMF on the longitudinal axis is achieved using cylindrical electromagnets positioned on the torch body coaxially with respect to the electrode [44]. However fabrication inaccuracies in components of torches and electromagnets, deflections from vertical position of both the arc, and the deformed electrode wire, greatly reduce the efficiency of such measures. Reduction of induction in the arc gap can be provided by placing the electromagnet at the underside of the weld. However, as in the former case, this does not exclude the occurrence of said negative effects. Besides, the latter solution is not always technologically efficient because of the necessity of both access to the back side of the welds along all their length, and joint travel of the torch and the electromagnet. Under conditions when it is impossible to limit the effect of CMF to only the pool melt, appropriate are the works aimed at increasing the efficiency of the considered EME, i.e. definition of positive effects of CMF created between the butt end of the electrode and the pool surface and their application in welding and surfacing techniques using EME; working out measures allowing to minimize or compensate typical negative effects.

So, in surfacing it is desirable to reduce the depth and the area of penetration of the base metal. In this case dispersal of the arc as the source of heating at EME is used to advantage for practically two-fold reduction of the depth of penetration [27, 45]. In consumable electrode welding depth of penetration is reduced for increasing the welding current, which increases the speed of melting of the electrode wire and raises productivity of the welding process.

Reduction of the depth of penetration in welding with EME is compensated by creating conditions where duration of basic-state arcing exceeds conic one. For this purpose in the zone of welding are generated pulsed CMF created by passing through the electromagnet coil of discrete current pulses of increased relative duration [26].

It will be noted that this method allows decreasing rather than in any way excluding the effect of penetration depth reduction. Thus for preserving the intensity of EME, increase in relative pulse duration should be accompanied by augmentation of CMF parameters. However, at constant induction the proportional increased duration of reversing intervals leads to deterioration of weld formation process parameters (on their surfaces form coarse overlaps, fusion lines have an variable shape) [2, 22]. At the same time, at the same interval of reversing, for generating greater inductions of CMF, it is necessary to increase mass and size of electromagnets. Besides, at increased relative duration of CMF pulses, the degree of inflexibility of EME mode decreases, that, in turn, somewhat reduces efficiency of their effect on the solidification processes. The above disadvantages demonstrate poor efficiency of the given method. Nevertheless it was successfully employed for producing filling welds in multipass welding [12].

Positive results in application of high-frequency CMF for controlling the process of mass transfer of the electrode wire were achieved in the arc dosing brazing and microsurfacing of high electroconductivity materials [28, 29]. For successful application of such EME in welding of structural steels, including high-alloy, a series of researches aimed at defining optimum parameter ranges of high-frequency CMF is necessary. At the same time still uncertain are the mechanism and the degree of positive effect of high-frequency CMF on the quality of welds. It is known that ultrasonic oscillations of the welding pool positively affect the processes of weld solidification. However, unlike this kind of external pulse effects, EME act without a physical contact with welding pool melt, which is their essential advantage. Therefore urgent is the task of defining the potential of achieving similar effects also using high-frequency CMF.

The potential for increasing efficiency of EME by arc oscillations and deviations produced by transverse CMF consists in providing for positive changes in the processes of solidification throughout the entire section area of welds. This is achieved by periodic changing during welding of the directions of the given pulse effects, namely by provision of oscillation-rotary movement of the arc [31]. Thus by regulating duration of the periods of its oscillation in the required direction, control of the processes of weld formation accompanied by both changes of their width and depth of penetration becomes feasible. This is a testimony of achieving a certain level of technological flexibility of the given EME. Implementation of such a process is possible only at the use of multipole electromagnetic systems.

At applying common techniques of wide-layer surfacing with EME using bipolar electromagnetic systems [35], non-uniformity of distribution of induction of CMF in the arc gap and over the working zone is observed. This leads both to the difference of speeds of travel of the anodic and cathodic areas of the arc (therefore stability of the arcing process essentially decreases), and to formation of the arc-shaped zone of penetration. Improvement of the given EME consists in elimination of the above negative effects. This can be achieved by generating of complex-shaped CMF pulses; by controlling distribution of induction over the working zone, or by changing the type of the arc travel from continuous to step-by-step with controllable lengths of the periods of arc immobility. It will be noted that the first former approach is much too complicated, whilst the other two is advisable to implement using multipolar electromagnetic systems.

Thus, application of non-combined CMF along with improvement of one group of weld quality parameters can produce some deterioration of others. Technological limitations of all most common methods of welding with EME are due to inherent for each of them negative by-effects, which existence is connected with different effects of CMF on the arc and the welding pool melt. Their partial compensation or minimization does not ensure essential increase of the efficiency of welding and surfacing techniques using EME.

The most essential increase of the efficiency of EME is achieved by the use of combined CMF. The considered above welding techniques are used for improving parameters of weld formation processes, but do not solve problems of overall improvement of quality of welded joints. However even given such restrictions, their technological opportunities are not exhausted.

So, in non-consumable electrode welding using combination of radial CMF by means of a quadrupole or other electromagnetic systems, it is feasible to compensate not only gravitational forces affecting the pool melt. Reversing the direction of the magnetic flux to the opposite leads to migration of the melt towards the pool bottom. Thus due to reduction of thickness of the liquid layer under the arc, the depth of penetration is increased [46].

It should be pointed out that superposition of axial reversive and stationary or alternating transverse CMF can deteriorate stability of arcing and parameters of weld formation. Under the given conditions promising is the method of combining consecutively (separated in time) generated in the zone of welding CMF having different vector characteristics, So, at consecutive generation in the zone of welding of reversive axial and transverse CMF, are produced separated in time flows of melt both in the horizontal plane along lateral surfaces, and in vertical plane along the top or bottom surfaces of the pool [47, 48].

At such EME efficiently influencing solidification processes, also control of the depth of penetration of welds by increasing or decreasing the thickness of the liquid layer under the arc is feasible. Growth or diminishing values of these parameters depends on the polarity of transverse CMF. Considering that at using axial CMF, it is possible to control the width of welds, application of such EME will allow most efficiently control the processes of their formation. Besides, at sufficient duration of action of transverse CMF, melt flows, moving in the vertical plane from the central area of the pool towards its tail part, reach solidification front, periodically creating there significant temperature gradients positively effecting the processes of weld solidification. Hence, with correct choice of combined EME parameters, periodic action of transverse CMF will not worsen the degree of positive effect of axial CMF on the processes of weld solidification. Such way of combining CMF is used for improvement of considered above EME by application of pulsed axial CMF [26]. In this case transverse magnetic field was generated not after the termination of intervals of action of axial, but rather after each their pulse during arcing under usual conditions. It has allowed reducing duration of reversing intervals of by reducing the pulse rate. Thus EME became more intensive and multipurpose [48].

For achieving overall improvement of quality parameters of welds, efficient also is consecutive combination of axial reversive and radial CMF causing longitudinal and transverse oscillations or arc deviations [48]. The mechanism of expanding technological opportunities in this case is similar to the above method. Thus it is necessary to comprehensively study the combination of which CMF is more efficient.

Maximal increase of the efficiency of EME in MIG / MAG welding can be achieved at combining axial reversive low- and high-frequency or pulsed CMF. Thus simultaneous control of the processes of solidification and transfer of the electrode wire metal becomes possible. In this case induced in the tail part eddy currents will promote improvement of dynamic characteristics of travel of melt flows along lateral fronts of solidification. Thus increase of the efficiency of effect of EME on the processes of solidification is to be expected. Presence of insignificant transverse constituent of induction of CMF in the area of melting of the electrode wire will not worsen the process of its transfer, but increase the force of droplet detachment. It assists in the growth of their detachment frequency and, as a consequence, increases the intensity of melting of the electrode wire.

CONCLUSIONS

1. Peak efficiency of EME in each concrete case is achieved by correct choice of controlling magnetic fields parameters. Thus axial CMF are more often applied for controlling solidification, while radial — by processes of weld formation.

2. Occurrence of negative by-effects in welding and surfacingå with application of traditional EME is connected with different effect of external magnetic

field on the arc as the heat source and droplets at the butt end of the electrode wire, on the one hand, and the pool melt, on the other. Their elimination is achieved by optimization of CMF parameters.

3. The most promising way of increasing efficiency of EME, ensuring overall improvement of the processes of formation and solidification of welds, is application of combined CMF. Carrying out further researches for all-round determination of the degree of the effect of such EME on the parameters of quality of welds in welding various classes of materials, is necessary.

1. Luo, J., Luo, Q., Lin, Y.H. et al. (2003) A new approach for fluid flow model in gas tungsten arc weld pool using longitudinal electromagnetic control. *Welding J.*, 82(**8**), 202–206.
2. Shelenkov, G.M., Chernysh, V.P., Gurevich, S.M. et al. (1977) Peculiarities of weld formation in arc welding of titanium with electromagnetic stirring. *Svarochn. Proizvodstvo*, **3**, 24–25.
3. Abralov, M.A., Abdurakhmanov, R.U., Yuldashev, A.T. (1977) Electromagnetic action on properties and structure of 01420 alloy welded joints. *Avtomatich. Svarka*, **5**, 21–24.
4. Abralov, M.A., Abdurakhmanov, R.U. (1980) Some peculiarities of formation of weld secondary boundaries in electromagnetic action. *Ibid.*, **2**, 12–14.
5. Abralov, M.A., Abdurakhmanov, R.U. (1982) On mechanism of refining of weld primary structure in electromagnetic action. *Ibid.*, **2**, 18–21.
6. Yakushin, B.F., Misyurov, A.I. (1979) Increase of technological strength in welding of medium alloy steel with electromagnetic action. *Svarochn. Proizvodstvo*, **12**, 7--9.
7. Boldyrev, A.M., Dorofeev, E.B., Antonov, E.G. et al. (1974) External magnetic field action on crystallization and technological strength in argon-arc welding of magnesium alloys. *Ibid.*, **9**, 14--16.
8. Igumnov, V.P., Maltsev, S.N., Konkov, Yu.D. et al. (1983) Consumable electrode gas-shielded welding with electromagnetic stirring. *Avtomatich. Svarka*, **3**, 41–42, 59.
9. Bardokin, E.V., Livenets, V.I., Okishor, V.A. et al. (1975) Structure and properties of weld metal in welding under low-frequency longitudinal alternating magnetic field. *Svarochn. Proizvodstvo*, **11**, 12–14.
10. Ryzhov, R.N., Maksimov, S.Yu., Prilipko, E.A. et al. (2005) Influence of external electromagnetic actions on the structure and composition of welds in wet underwater welding. *The Paton Welding J.*, **11**, 34–35.
11. Chernysh, V.P., Pakharenko, V.A., Kuznetsov, V.D. (1980) Influence of electromagnetic stirring condition on chemical microheterogeneity of welds. *Avtomatich. Svarka*, **1**, 76–77.
12. Briskman, A.N., Gladyshko, V.S., Kuznetsov, V.D. et al. (1973) Automatic welding of products of large thick steel Kh17N13M3T with electromagnetic stirring of molten pool. *Khimich. i Neft. Mashinostroenie*, **9**, 25--26.
13. Chayun, A.G., Syrovatka, V.V., Matyash, V.I. (1981) Arc welding of aluminium alloy 01420 with electromagnetic stirring. *Avtomatich. Svarka*, **6**, 19–21.
14. Ryzhov, R.N., Kozhukhar, V.A., Maksimov, S.Yu. et al. (2004) Application of external electromagnetic actions for improvement of mechanical properties of welds in underwater wet welding. *The Paton Welding J.*, **11**, 49--51.
15. Ryzhov, R.N., Skachkov, I.O., Chernysh, V.P. (1997) Increase of resistance of welds to hot cracking in manual consumable electrode arc welding. *Avtomatich. Svarka*, **4**, 25–29.
16. Czernyzh, W., Ryzhov, R., Tyrec, E. (2004) Influence of electromagnetic effect in welding on the increase in resistance to hot cracking. *Welding Int.*, **18**, 257–262.
17. Boldyrev, A.M., Birzhev, V.A., Muraviev, R.V. et al. (2001) Influence of external magnetic field on weld tightness in welding of OT4-1 alloy. In: *Abstr. of Conf. on Welding and Control* (2001). Voronezh: VGASU.
18. Maksimov, S.Yu., Prilipko, E.A., Ryzhov, R.N. et al. (2003) Effect of external electromagnetic action on hydrogen content in weld metal in wet underwater welding. *The Paton Welding J.*, **6**, 41–43.
19. Zavialov, V.E., Zvorono, Ya.P., Petrakov, A.B. (1990) Application of longitudinal magnetic field in submerged-arc surfacing. *Svarochn. Proizvodstvo*, **2**, 3–5.
20. Chernysh, V.P., Matyash, V.I. (1990) Prevention of disturbances of weld formation in increased welding speed and variable gap. *Avtomatich. Svarka*, **9**, 9–11.
21. Boldyrev, A.M., Birzhev, V.A., Pomerantsev, A.S. (2004) About possibility of process control during arc welding and surfacing in axial magnetic field. In: *Abstr. of Conf. on Welding and Control* (2004), Vol. 2. Perm: PGTU.
22. Shaferovsky, V.A. (1996) Influence of axial magnetic field on arc penetrability in welding of steel plate with mode programming. *Avtomatich. Svarka*, **8**, 20–24.
23. Manabe, Y., Zenitani, S., Hiromoto, Y. et al. Basic concept and viability of electromagnetically controlled molten pool welding process. *IIW Doc. XI, XII*.
24. Boldyrev, A.M., Birzhev, V.A., Chernykh, A.V. (1991) Peculiarities of electrode metal melting in welding with external longitudinal magnetic field. *Svarochn. Proizvodstvo*, **5**, 28–30.
25. Boldyrev, A.M., Birzhev, V.A., Chernykh, A.V. (2001) Melting of electrode wire in welding with axial alternating magnetic field of 50 Hz commercial frequency. In: *Abstr. of Conf. on Welding and Control* (2001). Voronezh: VGASU.
26. Malinkin, I.V., Popovsky, V.Yu., Syrovatka, V.V. et al. (1971) Maintaining of penetration deep in electromagnetic stirring conditions of weld pool. *Avtomatich. Svarka*, **8**, 46–48.
27. Boldyrev, A.M., Birzhev, V.A., Chernykh, A.V. (1993) Control of deep penetration in arc welding and surfacing with longitudinal alternating magnetic field. *Svarochn. Proizvodstvo*, **6**, 30–31.
28. Tarasov, N.M., Kapustin, S.S. (1982) Application of high-frequency electromagnetic field for dosed electrode metal drop transfer. *Avtomatich. Svarka*, **8**, 10–12.
29. Tarasov, N.M. (1984) Energy calculation of process of electrode metal droplet detachment under action of external magnetic field pulse. *Ibid.*, **6**, 21–25.
30. Zavialov, V.E., Ivantsov, V.Ya., Skornyakov, V.Ya. et al. (1979) Argon-arc welding of stainless steels using the magnetic fields. *Svarochn. Proizvodstvo*, **12**, 19–20.
31. Ryzhov, R.N., Semenyuk, V.S., Titov, A.A. (2004) Peculiarities of formation and crystallization of welds in TIG welding with magnetic arc deflection. *The Paton Welding J.*, **4**, 14--17.
32. Kovalev, I.M., Rybakov, A.S., Isakov, A.S. et al. (1977) Arc welding of cable sheathes in transverse magnetic field. *Svarochn. Proizvodstvo*, **11**, 37–38.
33. Kovalyov, I.M., Krichevsky, E.M., Lvov, V.N. (1975) Consumable electrode argon-arc welding of 1Kh18N10T steel pipes with weld formation in transverse magnetic field. *Ibid.*, **5**, 15--17.
34. Kang, Y.H., Na, S.A. (2003) Characteristics of welding and arc signal in narrow groove gas metal arc welding using electromagnetic arc oscillation. *Welding J.*, **3**, 93–99.
35. Razmyshlyaev, A.D., Maevsky, V.R. (1996) Effect of controlling magnetic fields on weld geometrical sizes in submerged-arc welding. *Svarochn. Proizvodstvo*, **2**, 17–19.
36. Kornienko, A.N. (1964) Magnetic control of submerged-arc strip electrode surfacing process. *Ibid.*, **4**, 12–14.
37. Eihhorn, F., Dilthey, U., Huwer, W. (1972) Unterpulver — Auftragschweissen mit 60–90 und 120 mm breiten Cr–Ni–Stahlbandelektroden. *Industrie:* Anzeiger, **98**, 2369–2372.
38. Akulov, A.I., Rybachuk, A.M., Chernyshev, G.G. (1979) Peculuarities of weld formation in welding with transverse magnetic field. *Svarochn. Proizvodstvo*, **7**, 11--14.
39. Rybachuk, A.M., Chernyshev, G.G. (1982) Influence of electrode immersion value on weld shape during welding in four-pole magnetic field. *Ibid.*, **2**, 25--26.
40. Brodyagina, I.V., Chernyshov, G.G. (1998) Arc welding of aluminium alloys with electromagnetic fields. *Ibid.*, **9**, 48–51.
41. Pakharenko, V.A. (1982) Calculation of optimal parameters of magnetic field in argon-arc welding with stirring of molten pool. *Avtomatich. Svarka*, **7**, 39–41.
42. Ryzhov, R.N., Kuznetsov, V.D. (2005) Choice of optimal parameters of external electromagnetic action in arc methods of welding. *The Paton Welding J.*, **6**, 24–27.
43. Ryzhov, R.N., Kuznetsov, V.D., Prilipko, E.A. (2005) Procedure of calculation of controlling electromagnetic action parameters in arc welding of structural steels. *Vestnik NTUU KPI*, **45**, 166–167.
44. Chernysh, V.P., Kukhar, S.N. (1984) *Equipment for welding with electromagnetic stirring*. Kiev: Vyshcha Shkola.
45. Razmyshlyaev, A.D. (1996) Influence of magnetic field on penetration sizes in submerged-arc surfacing. *Avtomatich. Svarka*, **8**, 25–27, 30.
46. Ryzhov, R.N., Kuznetsov, V.D., Malyshev, A.V. (2004) Application of six-pole electromagnetic system for control of weld formation parameters in non-consumable electrode welding. *The Paton Welding J.*, **2**, 41–44.
47. Ryzhov, R.N. (2005) Application of combined electromagnetic actions for improving the quality of welds in welding with non-consumable electrode. *Ibid.*, **7**, 52–53.
48. Ryzhov, R.M. (2005) Principles of volume control of weld pool solution hydrodynamics. *Naukovi Visti NTUU KPI*, **4**, 83--87.

ENSURING SAFE OPERATION OF EQUIPMENT FOR FLAME TREATMENT OF METAL

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Some design-technological and standard aspects of ensuring safe operation of the equipment for flame treatment of metals are described, taking into account, in particular, the need to prevent of internal flame burning in cutters and torches.

Keywords: flame treatment, equipment, injection, flap, flashback, internal (burning) combustion, blowback, fire safety valve

Ensuring of stable flame burning without flaps or blowbacks is an obligatory and one of the main demands in normative document of the system of standards on labour safety when using flame equipment [1, 2]. Unfortunately, the demands in the mentioned normative documents do not include a quantitative evaluation and do not take into account such a factor as flame internal burning in cutters and torches.

Investigations, carried out in the DONMET plant laboratory, showed that safety of flame equipment in operation is provided when such phases of burning as flame flap, internal burning and blowback are absent.

Flame flap develops instantly and leads to the flame dying down or its transition into internal burning or blowback. Equipment destruction does not happen in this case.

Internal burning represents stable burning of the combustible mixture inside of torch tip. The probability of destruction (burnout) of torch tip in the area of mixing chamber (Figure 1) exists at internal burning for 5–10 s from the moment of fire flap.

Blowback is penetration of the shock wave through the torch handle into the gas supplying hose and into gas cylinders. Rupture or burnout of gas supplying hoses, breakdown of the reducer or even gas cylinders explosion can be the results of back impact (Figure 2).

Flame flap that is the moment of the flame front transfer from outside into the inside of the nozzle, will certainly precede initiation of any of these phases. Flame flap is followed by flash burning of combustible mixture inside the torch tip that is accompanied by combustion product flying out into the atmosphere as well as into the torch gas- and oxygen-supplying channels, resulting in a short-time interruption of combustible mixture formation. If the remains of the old combustible mixture did not have time to burn down by the moment of new combusible mixture formation, then newly formed mixture ignites and burns inside the torch with the characteristic whistle sound that is the feature of internal combustion. Development of burning process after the flame flap can be conditionally divided into the phases that are mentioned below.

Burning phase, i.e. flame flap, occurs instantaneously in the torch tip with the following explosion of gas mixture.

Combustion product expansion phase starts simultaneously with the burning process and is manifested in outflow of combustion products through three channels: nozzle channel into the atmosphere *1* (does not stop during the whole process of burning); central hole of injector into the channel of oxygen supply (backflow) *2*; through side holes of the injector into the channel of combustible gas feed (backflow) *3* (Figure 3). Isothermal gas expansion with their outflow through the mentioned channels goes on until the pressure of combustion products in the torch tip exceeds the pressure in any of the gas supplying channels.

The phase of gas mixture formation resumption is characterized by that the pressure combustion prod-

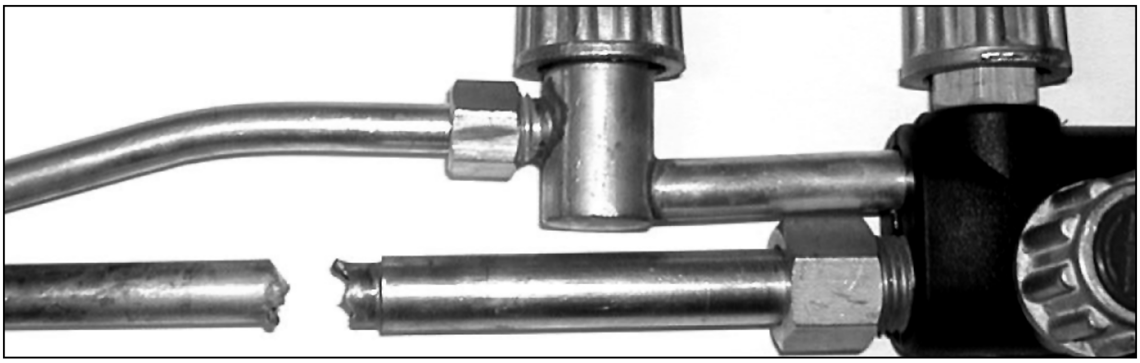

Figure 1. Tip tube burnout as a result of inner combustion

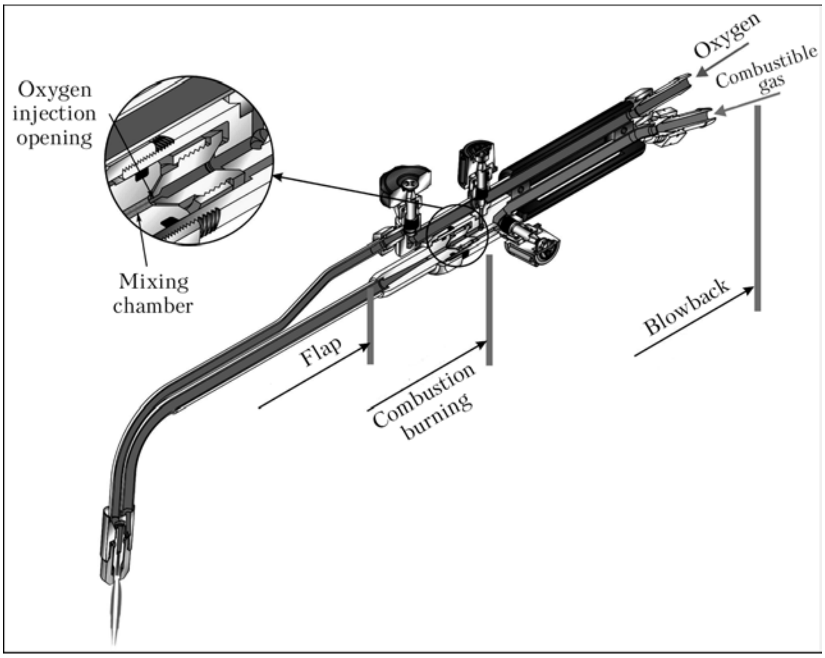

Figure 2. Nature of burning area expansion after flame flap

ucts in the torch tip drops after their expansion and the direction of gas flow in the torch channels is restored. A mixture of combustion products with oxygen, to which combustible gas is added, is drawn into the mixing chamber by oxygen injector jet and only after this the combustible gas is supplied in its pure form; then the gas mixture is formed and filling of the torch tip cavity takes place that is accompanied by displacement of the remaining combustion products. Burning of the newly formed mixture can start even before complete ousting of the combustion products in the presence of their remains in the mixture.

Investigation of parameters influencing the flame flap transition into inner combustion or blowback, and elaboration of design and technological recommendations on their basis that lower the probability of inner combustion or blowback after flame flap, should become the main direction in manufacture of flame equipment for ensuring its safe operation.

The demands to cutter design were defined more precisely by the results of investigations carried out in the DONMET plant pilot laboratory.

The reasons for initiation and methods of flap prevention are well known, being the speed of combustible mixture outflow from the nozzle, cleanness of the nozzle inside surface and its temperature, as well as design features of gas mixing unit.

The blowback occurs as a result of combustible mixture (combustible gas + oxygen) being present in the hoses and cylinders. The following causes for combustible mixture penetration into the sleeves and cylinders are established:

- cylinder was filled with oxygen after it had been filled with combustible gas or by combustible gas after it had been filled with oxygen;
- hoses earlier, used for feeding combustible gas or liquid fuel, were then used for oxygen supply;
- backflow of oxygen exists into the gas channel and then into the hose, etc. is in place.

The first two reasons are the result of gross violation of the rules of operation of the equipment for flame metal treatment, and can be prevented through organizational and technical measures.

To avoid the oxygen backflow into the gas channel, it is necessary to apply check valves. Their design, however, does not allow stopping the flame blowback.

Fire safety valves, which incorporate a metal-ceramic flame extinguishing insert in addition to the

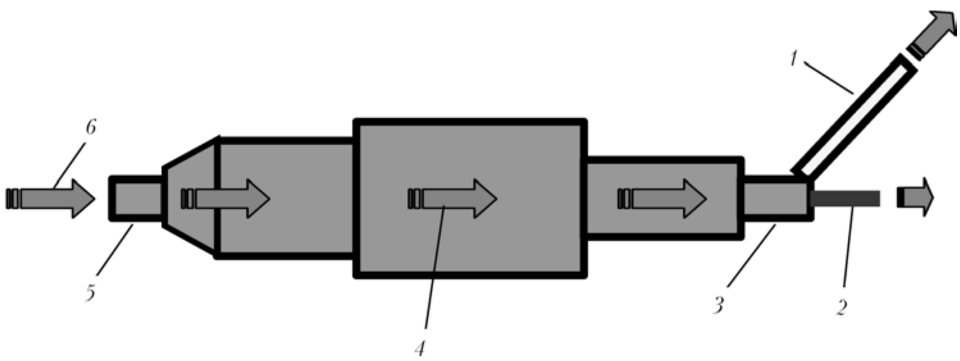

Figure 3. Diagram of gas flow into torch channels after flame flap: *1* — combustible gas channel; *2* — injection channel; *3* — mixing channel; *4* — in tip tube; *5* — in nozzle; *6* — flame front motion

check valve, are applied for extinguishing the flame at blowback with the aim to prevent its penetration into the cylinders.

Unfortunately, no requirements of obligatory use of check valves are included into the normative documents on labour safety [1, 2], they are absent also in the international standards.

The main method for ensuring safe operation of torches and cutters are the design features of their channels along which gas and oxygen flow before and after mixing. Taking into account the physical features of the burning process, it is possible to control the consequences of flame flap for prevention flame flap developing into stable combustion burning by means of design measures.

Specialists of the DONMET plant designed a procedure of quantitative evaluation of torch and cutter safety that allows evaluation of the technical solutions that provide resistance to flame flap and internal combustion in the entire range of operating pressures of combustible gas and oxygen to GOST 5191–79.

CONCLUSIONS

1. Equipment for flame metal treatment (cutters and torches) should have design protection with the aim of safe operation due to which probability of inner combustion or blowbacks after fire flaps are prevented.

2. Normative documents do not specify quantitative evaluation of torches and cutters safety level, or an obligatory registration of all the factors providing labor safety in operation of flame equipment. So, application of fire safety valves is just a recommendation. Updating of the normative documents in force is required.

1. *GOST 12.2.008–75 SSBT*: Equipment and apparatuses for flame treatment of metals and thermal spraying. Introd. 01.01.82.
2. *GOST 5191–79*: Injector torches for manual oxygen cutting. Introd. 01.01.77.

SYSTEM VEDN-1 FOR HIGH-VELOCITY ELECTRIC-ARC SPRAYING OF COATINGS

The system comprises electric arc metalliser, wire feed mechanism and power supply. The equipment is mobile and can operate both in manual and mechanised modes. Compared with traditional electric arc equipment, the system with the spraying unit of a new design provides increase in the velocity of a high-temperature jet, possibility of formation of contracted gas plume, increased density and low oxidation degree of coatings, as well as high strength of adhesion to the substrate:

Specifications of system VEDN-1

Operating current, A	50–400
Operating arc voltage, V	17–40
Wire feed speed, m/min	2–12
Working pressure of compressed air, MPa (kgf/cm^2)	0.5–0.7 (5–7)
Compressed air flow rate, m^3/h	90–120
Productivity, kg/h:	
aluminium or its alloys	12.5
zinc	40.0
Weight of electric arc metalliser (gun), kg	1.5
Material utilisation factor	0.75

The equipment is intended for deposition of wear- and corrosion-resistant, as well as special coatings, repair of worn out machine parts by spraying of electrically conducting materials made in the form of wire 1.6–2.2 mm in diameter. Thickness of the deposited coatings ranges from 0.05 to 5 mm. Compressed air is used as a working gas. A wide range of wires of aluminium, zinc, copper, bronze, brass, steel, as well as composite and flux-cored wires are applied for coating.

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PRODUCTION OF WELDING CONSUMABLES IN 2005 IN THE CIS COUNTRIES*

In estimation of the status of production of welding consumables in 2005, one should note the positive trends caused primarily by a general increase in output of competitive welding consumables, development and introduction of new welding consumables and process equipment, increasing application of advanced processes, etc.

The growth of output of welding consumables is determined to a considerable degree by manufacturing of industrial and building products, steel and rolled stock, first of all in Russia and Ukraine. Thus, metallurgists of Russia produced 64.87 mln t of steel and 54.4 mln t of rolled stock in 2005. The increase is insignificant compared with 2004: 1 % for steel and 1.5 % for rolled stock. Ukraine produced 38.6 mln t of rolled stock (the volume of production of steel was 99.8 %, and that of rolled stock was 100.5 %, compared with 2004).

The total volume of production of covered welding electrodes in 2005 in the CIS countries was 305,900 t, 79 % of it being produced by enterprises of the Russian Federation, 17 % — by enterprises of Ukraine, and 4 % — by the rest of the CIS countries. This is indicative of a 5 % increase in a total volume of production, including 7 % in Russia, and 3 % in Ukraine. The output of electrodes as to the covering type was as follows: rutile-ilmenite electrodes — 174,600 t, and basic electrodes — 108,100 t. The volume of production of special-application electrodes for welding high-alloy steels and non-ferrous metals was 23,800 t, the growth being 48 %.

The volume of production of electrodes in 2005 in Russia was 240,400 t, including 120,100 t of rutile-ilmenite electrodes, 97,500 t of basic electrodes, and 22,800 t of special electrodes. Accordingly, Ukraine produced 53,000 t of electrodes, including 42,000 t of rutile-ilmenite electrodes, 10,300 t of basic electrodes, and 1,000 t of special electrodes.

The positive trend is currently towards increase in production of small- and medium-diameter (2–4 mm) electrodes. Their output has totally amounted to 270,100 t, the increase being 4.6 % compared with 2004. The volume of production of 5 and 6 mm diameter electrodes was 36,300 and 25,000 t, respectively.

The total output of alloyed welding wire up to 2.0 mm in diameter, intended for mechanised gas-shielded welding, was 45,200 t, including 25,360 t of 0.8–1.4 mm diameter wire. Russia produced 33,400 t, including 18,200 t of 0.8–1.4 mm diameter wire; and Ukraine produced 11,800 t, including 7,200 t of 0.8–1.4 mm diameter wire.

Compared with 2004, the total output of wire in the CIS countries decreased by 8 %. At the same time, Russia increased it by 2 %, and Ukraine decreased by 35 %. In particular, we have to emphasise the tendency to growth of production and consumption of copper-coated wire, which is supplied by orders in required quantities in spools and reels with row winding, from 5 to 15 kg or more in weight. Main suppliers of this wire are the Association member companies, such as «Mezhgosmetiz-Mtsensk», «MMK – Metiz», «ChSPZ», «OSPZ», and «Severstal-Metiz». The output of copper-coated wire in 2005 was 12,600 t, the increase being 217 % compared with the last year.

The amount of welding and surfacing wire produced in 2005 was 4401.8 t, including 1996.3 t of welding wire, 2965.2 t of surfacing wire, and 200 t of flux-cored surfacing strip. Compared with 2004, the volumes of their production remained almost at the same level. In Russia, the output of flux-cored wire was 2965.2 t, including 1380.2 t of welding wire, and 1585 t of surfacing wire. Ukraine produced 1436.6 t of flux-cored wire, including 616.1 of welding wire, 620.5 t of surfacing wire, and 200 t of strip.

The output of welding fluxes in 2005 was 37,779.8 t, including 12,472.8 t in Russia, and 25,307 t in Ukraine. Russia increased the volume of production of welding flux by 18 %, and Ukraine decreased it by 4 %, compared with 2004.

In 2005, the total output of welding consumables was 393,280 t, including 87,465 t of consumables intended for mechanised welding. Consumables for mechanised welding constitute 22 % of the total output.

The above data confirm the general growth of production of welding consumables, including for mechanised welding processes.

*The article is based on proceedings of an enlarged meeting of the Board of Directors of Association «Electrode» of the CIS countries enterprises (Bor, Nizhny Novgorod oblast, May 3–6, 2006).

59th ANNUAL ASSEMBLY OF THE INTERNATIONAL INSTITUTE OF WELDING

Ukrainian delegation members at the national flag

59th Annual Assembly of IIW was held in Quebec, Canada, from August 27 to September 2, 2006. The Assembly organizer was the Canadian Council of IIW. About 400 delegates from 39 countries participated in the Assembly activities. Out of 48 IIW member-countries the delegations of Argentine, Greece, Israel, Lebanon, Libya, New Zealand, Pakistan and Chili were absent from the Assembly. Japan (59 persons), USA (45 persons) and Germany (38 persons) sent over the largest delegations, which has been the case for the last 15–20 years. By the number of the delegates they were followed by Canada (28), Sweden (26), England (17), France (15), Australia (12), Ukraine (12), Slovakia (10), and Finland (10). Delegations of other countries consisted of 2–3 persons.

Considering that more than 20 Commissions and other structural divisions were set up at IIW to ensure effective work and familiarization with the state-of-the-art in the welding field, the national delegations should consist of at least 8–10 specialists, each of whom should participate in working meetings of 2–3 Commissions.

Today IIW Commissions and structural units include: C-I — brazing and soldering, thermal cutting and flame treatment processes; C-II — arc welding and welding consumables; C-III — resistance welding and cold welding, as well as allied processes of material joining; C-IV — beam welding processes; C-V — monitoring and assurance of welded structure quality; C-VI — terminology; C-VIII — labour safety; C-IX — material behaviour in welding; C-X — welded structures, fracture prevention; C-XI — pressure vessels, boilers and pipes; C-XII — arc welding processes and technologies; C-XIII — fatigue strength of weldments and structures; C-XIV — education and training; C-XV — design, analysis and fabrication of welded structures; C-XVI — polymer welding and adhesive bonding technology; 1AB / A — education, training and certification; 1AB / B — introduction and accreditation; SC-AIR — permanent joints for advanced materials and coatings for aircraft construction; SC-AUTO — motor transportation; SC-ENV — environment; SC-QUAL — quality assurance in welding and related technologies; SC-STAND — standardization; SC-UW — underwater welding; SG-212 — physics of welding; SG-RES — strategy of investigations in welding and co-operation.

During the official opening of the Assembly, international awards were handed over to a number of scientists for the most outstanding work in the field of welding and related technologies. This year the Evgeny

IIW member-countries (for July 2006)

Europe		America	Africa / Asia / Oceania
Austria	Italy	Argentine	Australia
Belgium	Norway	Brazil	China
Bulgaria	Poland	Canada	Egypt
Croatia	Portugal	Chile	India
Czeckia	Rumania	Mexico	Indonesia
Denmark	Russia	USA	Iran
Finland	Serbia		Israel
France	Slovakia		Japan
Germany	Slovenia		Lebanon
Great Britain	Spain		Lybia
Greece	Sweden		Malasia
Holland	Switzerland		New Zealand
Hungary	Ukraine		Pakistan
			Singapore
			South Africa
			Tailand

Paton International Prize was awarded to Dr. Alan Sanderson (UK). On behalf of IIW and the Ukrainian National Committee on Welding, the Prize was presented by K.A. Yushchenko, academician of NASU.

The first three days of Assembly activities were devoted to meetings of the Commissions, working groups and other IIW subdivisions. Ukrainian representatives participated in the work of Commissions I-VI, IX-XV, SC-STAND, Council on International Qualification and Certification of Welding Production Personnel (IAB), as well as in the work of SG-212 research group. Seven presentations were made from PWI (K.A. Yushchenko — 4, L.M. Lobanov — 1, V.E. Ponomarev — 1, I.V. Zyakhor — 1), which attracted great interest.

In the meeting of the Council on International Qualification and Certification of Welding Production Personnel the Certified National Body (CNB) of Ukraine (which was organized on the basis of PWI Interindustry Educational-Certification Center) received thanks for the assistance rendered to the Welding Society of Brazil in preparation of a documentation package for the application for joining the IIW harmonized system on training and certification of welding production personnel. Brazil became the 33rd country, which introduced the international system of training the welding production personnel. The other countries already having CNBs are Australia, Austria, Great Britain, Belgium, Bulgaria, Hungary, Denmark, Germany, Holland, Iran, Spain, Italy, Canada, China, Norway, Poland, Portugal, Russia, Rumania, Slovakia, Slovenia, Tailand, Ukraine, Finland, France, Chroatia, Czechia, Switzerland, Sweden, Yugoslavia, South Africa and Japan.

One of the items on the agenda for the meeting of the Council on International Qualification and Certification of Welding Production Personnel was consideration of the Guidelines and Program of training the **Welded Structure Designer**. It is intended to introduce two qualification levels, namely full level designer (training course duration of 180 h), and standard level designer (training course duration of 102 h). Specialists which have assimilated such a course, will be capable of designing welded structures considering the conditions of their operation and features of welding performance. Guidelines and programs of training the International Engineer, Technologist, Specialist, Practitioner, Welding Inspector, as well as International Welder have been prepared by now within the IIW harmonized system on training and certification of welding fabrication specialists.

Presentation «On upgrading the «Classification of Metal Transfer» by D. Iordashesku (Spain), V. Lucas (Great Britain) and V. Ponomarev (Ukraine) attracted great interest and led to a lively discussion. By now the current classification of the types of electrode metal transfer in fusion welding, which was suggested in 1984 is obviously outdated, as during this time the features of metal transfer were studied more profoundly with application of up-to-date research instruments, and, on the other hand, several variants of controllable metal transfer have been developed over the last years, which also need to be classified. As a result of the discussion, a decision was taken about setting up a working group for development of an up-to-date classification of the modes of electrode metal transfer.

Presentation of Evgeny Paton International Prize

One of the positive features of this IIW Assembly is a higher interest of industry representatives to the activities of Commissions on different directions of welding development. For instance, out of eight members of Austria delegation four represented the Fronius private company, manufacturing electric welding equipment.

In this Assembly K.A. Yushchenko was appointed a member of IIW International Commission «Road Map». The Commission objective is to perform analysis and taking into account the priority directions of development of the main industries, define the goals for the period up to 2015, which are to be achieved in welding in different countries (industrialized, developed and developing) and methods of their realization.

After completion of the activities of IIW 59th Assembly an International Conference on «Tubular Structures» was held (August 31–September 2, 2006), in which more than 80 papers were presented in the following sessions: fatigue fracture, joint strength under static load, strength of load-carrying structure elements, composite material structures, casting steels, seismic-resistant structures.

The next Assembly is to be held on July 1–7, 2007 in the city of Dubrovnik, Chroatia. In 2010 Ukraine will have the honorary mission of organizing the IIW Assembly.

V. Ponomarev

Prof. V.I. MAKHNENKO IS 75

In October academician of the NAS of Ukraine Vladimir I. Makhnenko turned 75. He started his labor activity at the shipbuilding plant in Arkhangelsk after graduation from Odessa Institute of Marine Engineers in 1955. After completion of the post-graduate course, V.I. Makhnenko was invited to work at the E.O. Paton Electric Welding Institute. Here, he defended the thesis for Doctor's degree in 1973, was elected a Corresponding Member in 1978 and an academician of the NAS of Ukraine in 1990.

Scientific activity of Prof. V.I. Makhnenko is inseparably linked with fundamental studies in the sphere of welding science. His gift as a scientist manifested in full measure particularly in this field. Owing to inexhaustible diligence, purposefulness, sense of the new and deep scientific intuition Prof. Makhnenko achieved a number of major scientific results, connected with the studies of heat, diffusion, deforming, electromagnetic and other physical phenomena in welding and in allied technologies.

Leading the Department of Mathematical Methods of Physicochemical Investigation Processes in Welding and Special Electrometallurgy since 1975, V.I. Makhnenko made a major contribution into establishment and development of the methods of mathematical modeling of welding processes and creation of modern systems of information support in the field of welding. Widely known are V.I.Makhnenko's studies on kinetics of multiaxial welding stresses and strains in welding plates, shells, rod systems, on calculation of the interaction of welding stresses and deformations with external operational loads of welded structure elements.

Under the supervision of V.I. Machnenko, a program package was designed that allows forecasting a complex of physical parameters in welding new structural materials that determine the welded joint quality: sizes and form of penetration zone, chemical composition and structure of the penetration zone, thermal cycles, microstructure and properties of HAZ, kinetics of stresses, plastic deformations and movements in the process of welding heating, risk of hot and cold crack formation, distribution of residual stresses and their influence on the ultimate load under static or alternating loading. Optimum variants of design and technological solutions for a number of new welded structures in cooperation with different industrial research institutes and industrial enterprises.

Over the last years, Prof. V.I. Makhnenko has actively worked on the urgent problem of residual resource evaluation and extension of service life of welded structures and constructions, including nuclear engineering facilities in Ukraine and the main pipelines. Preparation and sending into publication of a book «Resource of Safe Operation of Welded Joints and Components of Modern Structures» is the result of effective development in this field.

V.I. Makhnenko is the author of more than 320 works, including 12 monographs. Many of his works were published in the USA, Great Britain and FRG.

Prof. Makhnenko generously shares his knowledge with the youth and is continuously involved in scientific staff training. He created a school of mathematical modeling of different welding processes and allied technologies, well-known in our country and abroad. Prof. V.I. Makhnenko has been delivering course of lectures «Strength of Welded Structures and Joints» to students since the time of formation of the Chair of Physical Metallurgy and Materials Science in the Moscow Physico-Technological Institute in 1988. Two Doctors and more than 20 Candidates of Engineering Sciences were trained under his supervision.

V.I. Makhnenko successfully combines fruitful research with science-organizational and public activity, being the Head of Science-Coordination Council on Residual Life and Safe Operation of Structures, Constructions and Mechanisms of the NAS of Ukraine, member of two specialized councils, member of Editorial Board of «Avtomaticheskaya Svarka» journal. A number of international conferences on modeling of welding processes were conducted under his direction during the last years.

V.I. Makhnenko was awarded the order of Friendship of Nations and medals. In 2004 V.I. Makhnenko was conferred the honorable title of «Honored Worker of Science and Technology of Ukraine» for considerable contribution into the development of domestic science and technique in the direction of modern welding structures creation and ensuring of the recourse of their operation.

International recognition of V.I. Makhnenko's contribution to welding science was manifested in his election as member of American Welding Society (AWS) and a member of International Federation of Quantitative Non-Destructive Methods of Evaluation (QNDE).

Prof. G.V. PAVLENKO IS 60

Georgy V. Pavlenko, General Director of Simferopol Electrical Engineering Plant of «SELMA» Company, Honored Machine Builder of Ukraine, academician of the Academy of Engineering Sciences of Ukraine, winner of the State Prize of Ukraine turned 60 on October 25, 2006.

G.V. Pavlenko graduated from Kharkov Polytechnic Institute in the specialty of electromechanical engineer. After military service in the Soviet Army, he began his working life as an engineer in Kharkov «Yuzhmontazh» Trust. Since 1974, his labor activity has been connected with Simferopol Electrical Engineering Plant, where he worked as a designer- engineer, Chief of Quality Department, chief engineer. In 1999 G.V. Pavlenko was appointed Technical Director and in 2002 Director General of «SELMA». G.V. Pavlenko showed himself to be a competent, experienced specialist, gifted organizer in all the positions.

In the time of his leadership of «SELMA», G.V. Pavlenko was directly involved in creation of 6–7 types of welding equipment annually. Range of produced products was renewed by 40 % during the last 5 years through his efforts. Under the supervision of G.V. Pavlenko, «SELMA» was the first of the enterprises of the Autonomous Republic of the Crimea to introduce the ISO 9001–2001 quality system.

G.V. Pavlenko constantly pays attention to personnel policy and improvement of the enterprise operation style. More than 120 new work places were created over 2002–2005, part of which were taken by the children of the plant employees. This is how worker dynasties are formed.

High standards of production hygiene, strict observance of safety rules, creation of non-polluting production conditions and environment is the style of «SELMA».

Social sphere is the object of constant care of the Director — holiday center «Paris» and children's summer camp, one of the best in Ukraine complex «Crimson Sails», medical center with modern dental care complex, plant dining room with reduced prices and many other facilities.

G.V. Pavlenko is one of the initiators of establishing the «PWI Technology Park». Successful fulfillment of innovation project «Development and setting up of serial production of the range of modern equipment for arc and plasma welding and cutting» in Technopark framework allowed attracting additional funds for the enterprise development, provided expansion of manufactured equipment range, improvement of production technology. Manufacturing of equipment and competitiveness in the world markets are increased, and export rises. The needs of home market are fully covered.

The evidence of successful work of «SELMA» was awarding the title of «Leader of industry and enterprise of Ukraine'2006» to the enterprise.

G.V. Pavlenko was awarded the Diploma of the Council of Ministers of Autonomous Republic of the Crimea for his great contribution to production and development of industry.

Owing to the high level of competence and humane qualities, G.V. Pavlenko has merited authority in the labor collective, among his colleagues and directors of Crimean enterprises.

Prof. V.I. LAKOMSKY IS 80

In October Victor I. Lakomsky, well-known scientist in the sphere of special electrometallurgy and welding, Corresponding Member of the National Academy of Sciences of Ukraine, Doctor of Engineering Sciences, winner of the State Prize of Ukraine, Honored worker of science and technology turned 80 years.

V.I. Lakomsky was born on October 11, 1926 in Kramatorsk, Donetsk region. He was graduated from Metallurgical Technical School in Novokuznetsk, Kemerovo region in 1945, and in 1950 from Zaporozhie Machine-Building Institute. After completing a post-graduate course at the Kiev Polytechnic Institute in 1954, he defended the Candidate's thesis and joined the Institute of Science of Machines and Agricultural Mechanics, where he worked in the position of Scientific Secretary of the Institute. V.I. Lakomsky has been working at the E.O. Paton Electric Welding Institute since 1957 up till now. In 1969 V.I. Lakomsky defended the thesis for a Doctor's degree, in 1971 his academic title of professor was cofirmed. In the period from 1975 till 1979 he was Deputy Director on scientific work of «UkrNIIspetsstal» Institute. In 1998 he was granted the title of Honored worker of science and technology.

V.I. Lakomsky's profound and substantial scientific studies in different spheres of technology (metallurgy, welding, materials science and other) won him the deserved recognition and high scientific authority. He is the author of original techniques of studying the equilibrium of the gas–liquid metal system with different heating methods in a wide range of temperatures: from the melting point to the boiling point of metals. He was the first to experimentally discover, theoretically substantiate and practically prove the possibility of metal alloying by nitrogen in a wide range of concentrations directly from the gas phase for the first time. Owing to these works, a whole scientific field was created and is successfully developing, namely investigation of the regularity of high-temperature interaction of gases in a normal oscillatory state and in arc and plasma excitation state, with liquid metals. Exactly such scientific approach to solution of real engineering problems allowed in a short time developing the theoretical fundamentals, technology and equipment, as well as introducing into industry one of the special electrometallurgy methods, namely plasma-arc remelting of metals and alloys. This work, conducted under the leadership of academician B.E. Paton, was marked by the State Prize of Ukraine in 1980.

The work on creation of fundamentally new self-sintering thermo-chemical cathodes and of electric arc heat sources — arctrons — on their basis, led to creation of a unique technology of open-arc welding of ferrous and nonferrous metals with carbonic materials. This technology is successfully used when manufacturing of multi-amperes contact units of electrometallurgical and electrothermal installations both in Ukraine and abroad.

The current stage of V.I. Lakomsky's scientific activity is connected with physical properties and technological aspects of thermoanthracite study that allows changing the design of electric calcinators and the technology of thermoanthracite manufacturing.

Prof. V.I. Lakomsky is the organizer of a number of scientific subdivisions of the Institute. He organized Gas in Metals Laboratory in 1958, in 1968 — the Department of Plasma Metallurgy, in 1979 — a subdivision of PWI in Zaporozhie, and in 1995 — the Scientific-Engineering Center of Plasma Technology.

Victor I. Lakomsky carries out an important work on training the scientific personnel. 11 Candidates of Engineering Science were trained under his supervision. He takes an active part in scientific life: makes presentations and delivers lectures, he is a member of Special Council on defending theses, a member of the Editorial Board of «Sovremennaya Elektrometallurgiya» journal.

V.I. Lakomsky published more than 500 scientific works among which there are more than 300 articles, 8 monographs and about 200 of Author's Certificates of inventions and patents, granted in different countries of the world.

Prof. V.I. Lakomsky is full of creative power, firmness of purpose in searching for new original solutions of the tasks faced by special metallurgy and welding.