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

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UNIQUE TECHNOLOGY DEVELOPED BY UKRAINIAN SCIENTISTS FOR ELIMINATION OF UNDERWATER ACCIDENTS IN OIL AND GAS PIPELINES

On the 3rd of December 2010 the E.O. Paton Electric Welding Institute of the NAS of Ukraine presented a revolutionary development made by the Ukrainian scientists: technology and facilities for prevention of disasters, such as that occurred in April 2010 in the Gulf of Mexico. The presentation was attended by representatives of the scientific community from a number of institutes of the NAS of Ukraine, the Chamber of Industry and Commerce of Ukraine, associates of embassies, and mass media. Representatives from the Administration of the President of Ukraine, ministries, agencies, L.K. Kadenyuk — pilot-cosmonaut of Ukraine, as well as representatives from oil-producing companies «Chevron», «Conoco Phillips», «Exxon Mobil», «Royal Dutch-Shell» and «British Petroleum» were also invited.

The presentation was opened by Prof. B.E. Paton. He evaluated the disaster that took place near the U.S. coast as the most large-scale one in the history based on the consequences for the environment — over a million of barrels of oil in water, pollution of the coast of four American states, losses of the «British Petroleum» Company and U.S. Government worth of billions, and contamination with oil followed by contamination with chemicals used to eliminate oil.

The oil and gas production technologies have been improved during the last thirty years. However, the methods for controlling the accident consequences have remained unchanged. Therefore, the tragedy in the Gulf of Mexico may recur in other countries as well. At the same time, people will not stop extracting hydrocarbons, as the demand for them will grow by 15–20 %, according to forecasts for the next ten years.

The disaster forced the world leading countries to take the unprecedented measures aimed at developing new approaches to prevent accidents in production of hydrocarbons in offshore areas. Leaders of the G-20 countries gave special consideration to this issue at the summit in Toronto, which was reflected in the statement of this summit. The European countries having territorial waters decided to revise the rules for companies involved in oil and gas production in their shelves. Reaction of the Russian Government to the accident in the Gulf of Mexico did not to take long to appear either. It repeated in many ways approaches of the American Side. One month after the accident in the Gulf of Mexico the Russian President charged the Government with working out of the «Protection of Russian Seas from Oil Contamination» Law, which had to regulate obligations and responsibilities of the producing companies in case of oil contamination of the Russian shelf.

In Ukraine, the oil and gas deposits in the Black Sea shelf have been exploited since the Soviet times, and now it is planned to explore new deposits. Moreover, there are huge deposits of noxious and explosive hydrogen sulfide gas in the Black Sea at a depth of more than 50 m. If a high pressure pipe fails at the bottom, it would cause an irreversible damage to the coats. N.Ya. Azarov, the Prime Minister of Ukraine, noted in this connection that «...after the catastrophe in the Gulf of Mexico, I have a question of the price. If such an accident had occurred in the Crimea, we would have lost not only the Peninsular, but also the entire Black Sea coats, starting from the border with Moldova and ending with the Taman. We have to think over this price very seriously».

The accident at the Deepwater Horizon forced the Caspian states to look in a new way at their plans to increase the volumes of extraction of hydrocarbons from the Caspian Sea deposits and their transportation to external markets by using tanker fleets.

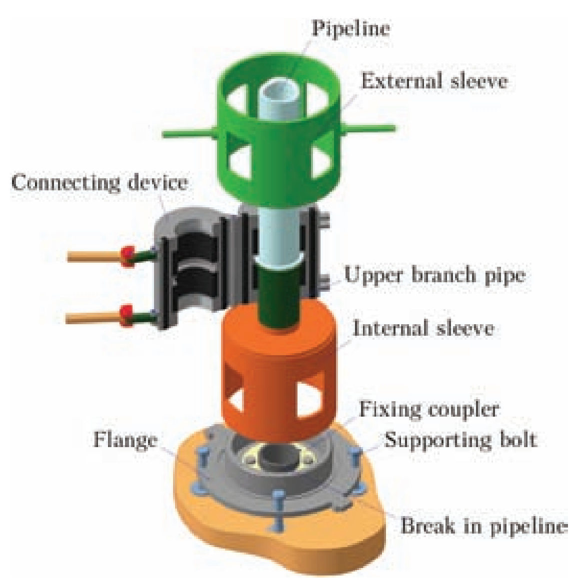
Turkey's Energy Minister Taner Yildiz pointed to the necessity to take the urgent measures to protect the Black Sea from catastrophes and accidents related to extraction and transportation of hydrocarbons. Turkish authorities are considering different tools to minimise threats of such events.

Address made by Prof. B.E. Paton

Turkey declared its intension to establish the foundation for protection of the Black Sea ducts. It is expected that foreign companies will take part in its formation. Contributions to the foundation can exceed 30 Billions of U.S. Dollars. This issue was discussed at the International Conference in Istanbul with representatives of twenty world-leading companies, including from Russia and Kazakhstan. The administrative decisions were followed by the technological ones. Four world oil companies — Exxon Mobil, Conocco Phillips, Chevron (USA) and Royal Dutch-Shell (British-Dutch Company) — decided to set up the system for elimination of oil spills in exploration of deepwater regions.

Ukraine is consistently pursuing a policy of ensuring international environmental safety. It supports initiatives of governmental and non-governmental organizations on prevention of accidents and ecological disasters related to extraction of hydrocarbons as the most hazardous material for the present and future of the mankind, being very active in development efforts in this sphere. Our state approached the international community with a proposal to unite and intensify efforts in addressing this problem, which is one of the most serious threats to the international safety. In his speech at the UN General Assembly Meeting in September 2010, the President of Ukraine declared a number of proposals of Ukraine in the sphere of international security.

Considering the necessity to guarantee safety in arrangement of extraction of hydrocarbons in the Black Sea shelf, as well as participation of our country in international projects, the Government of Ukraine entrusted the National Academy of Sciences of Ukraine, together with the High-Technology Education and Research Centre of the National Defence University of Ukraine, to develop technologies for prevention or, in the case of occurrence, elimination of such accidents in the shortest possible time with minimal consequences for the environment.

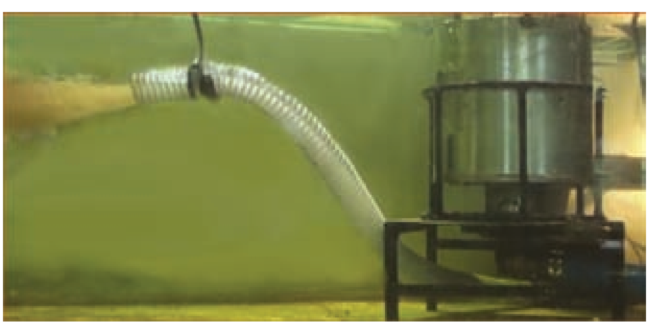


Model of the emergency module

Authors of the development answer questions from reporters

The scientists of Ukraine found the answer to the question how accidents in the coastal shelves can be quickly and efficiently eliminated. Prof. B.E. Paton noted at the presentation: «We made the development... and suggest that Ukraine should add it to its arsenal for off-shore oil production and for application abroad. The Ukrainian technology is fundamentally new. It allows solving one of the most important problems of protection of the environment».

The team of the authors proved to be surprisingly harmonious and mutually complementary. As in a well-organised crew, everybody played his role. Boris Paton, Director of the E.O. Paton Electric Welding Institute and President of the National Academy of Sciences of Ukraine, managed performance of the team like an orchestra conductor, introducing elements of his wisdom, experience and intelligence to every part of the development. Colonel Yu.G. Danik, Head of the High-Technology Education and Research Centre of the National Defence University of Ukraine, together with Prof. B.E. Paton generated ideas, principles and variants of their realisation. These ideas were inventively picked up and practically implemented in design documents and working models by V.I. Stepakhno, Doctor of Physical-Mathematical Sciences, Chairman of the Board of Directors of the Pilot Plant for Welding Equipment of the E.O. Paton Electric Welding Institute, and V.S. Romanyuk, Laureate of the State Prize of Ukraine in the field of science and technology, Director of State Enterprise «Experimental Design Bureau of the E.O. Paton Electric Welding Institute».



Connection of the module to the emergency well for further transportation of fluid via the pipeline

Process of connection of the module to the emergency well in hydraulic pool

Yu.G. Danik, one of the authors of the development, said the following about it: «We succeeded in looking at the problem from a new point of view. Consider, for example, the accident in the Gulf of Mexico. The seal of the wellhead failed as a result of explosion at the oil producing platform and fire that followed, and oil gushed out into the sea at a high pressure. How the liquidators of accidents behave in such cases? All of the existing approaches are based on closing, stopping and sealing the leak. To overcome resistance of the powerful natural force means actually to do violence to the nature. But will it guarantee that the leak will be stopped forever? Not at all. There are about thousand and a half suspended wells in the Caspian Sea that continue leaking. And the leak in the Gulf of Mexico has not been fully eliminated either. We used an absolutely different principle to serve as a basis of our technology. It is necessary to be on friendly terms and cooperate with the nature, turn its force in the required direction, and control it».

Patent engineers of the E.O. Paton Electric Welding Institute conducted preliminary search and determined that our principle is applied in none of the known patented inventions. Based on this principle, the team of the scientists developed the emergency module of a special design, resembling in a way a docking module of a spacecraft. It is connected to the leakage location, compensates for the impact blow of a leaking substance, and carefully redirects the flow along the required path. This allows the leak to be stopped and extraction to be continued. The module can be installed by using robots, or it can be a robot itself.

If all of the producing platforms are equipped with such modules, this will make it possible not only to quickly eliminate various-scale accidents, but also to resume production of oil and gas at the suspended emergency platforms and fields, the potential of which is far from being exhausted. The development made by the Ukrainian scientists will solve the problem of ensuring the international environmental safety in extraction of hydrocarbons, and will promote further advancement of this extraction.

The development had to be experimentally tested. The Institute of Hydromechanics of the NAS of Ukraine made preliminary calculations. The Experimental Design Bureau of the E.O. Paton Electric Welding Institute prepared design documents, and specialists of the Pilot Plant for Welding Equipment made working models of the module. The tests were conducted with the simulated well, from which a flow of fluid gushed out at a preset rate and intensity. The experiments were successfully completed, thus proving the effect of the principle. V.S. Romanyuk, one of the authors of the development, shared impressions about the tests at the presentation: «As soon as we performed the connection, the flow became controlled. We used the rotation mechanism to close the flow gushing out into the environment and directed it along the required path. It can be a pipeline, container, etc.».

A video illustrating sequential simulation of the operations on «taming» the blowout of oil from the well and redirecting it along the require path, as well as other video materials on testing the method and facilities offered by the Ukrainian scientists at the laboratory rig of the Institute of Hydrodynamics were demonstrated during the presentation.

The floor at the presentation was also taken by V.I. Stepakhno, Director of the Pilot Plant for Welding Equipment, L.K. Kadenyuk, pilot-cosmonaut of Ukraine, Prof. V.T. Grinchenko, Director of the Institute of Hydromechanics, V.A. Kolyadenko, Vice-President of the Ukrainian National Committee of the Chamber of Industry and Commerce, and V.I. Lakomov, Director of the Department for Foreign Economic Cooperation at the Ministry of Foreign Affairs.

The presentation attracted a keen interest in the subject being discussed and in the proposal of the Ukrainian scientists. Some reporters put questions to the developers of the accident elimination method concerning further promotion of this development and its potential economic attractiveness for Ukraine.

Prepared by TPWJ Editorial Board

INDICATORS OF STABILITY OF THE GMAW PROCESS

Yu.N. LANKIN
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Formulation of the term of stability of the GMAW process is offered. Objective indicators of stability are considered and analysed. A set of indicators of the process stability is suggested for each welding method and character of metal transfer.

Keywords: *arc welding, metal electrode, welding process quality, welding process stability, indicators of stability*

One of the main indicators of quality of the gas metal-arc welding (GMAW) process is its stability, which is closely related to such quality indicators as spattering and quality of weld formation. No generally accepted formulation of the notion of stability of the welding process exists now. Every researcher understands stability of the process in his own way and, therefore, uses differing indicators of stability.

The purpose of this study is to formulate the notion of stability of the GMAW process and choose the indicators of stability depending on the welding method and type of transfer of the electrode metal into the weld pool.

Several different definitions of the «welding process stability» term are available. GOST 25616–83 (ST SEV 3235–81) mentions the «welding process stability» term only for manual stick electrode welding, but gives no formulation for it [1]. Later on, developers of these standards formulated the «welding process stability» term for manual and mechanised welding as follows [2, 3]: «Term «the stable welding process» implies a process which provides quality formation of a welded joint with the sufficiently smooth surface and main parameters that are practically constant along its entire length — penetration depth, and bead width and height». The authors of study [4] offered a close definition: «It is generally agreed that the stable welding process is a process which provides constancy of geometric sizes of the weld or their deviation within the permissible limits». In fact, this is a formulation of a consequence of stability of the welding process, rather than the stability of this process. According to this formulation, it is very difficult to automatically measure stability indicators directly during the welding process.

In the broad sense the Latin word «stabilis» means constant, steady. For example, studies [5–8] make no difference between notions «stable» and «steady», while study [9] gives the following definition: «The spatial steadiness of the arc is called stability of the arc». However, terms «stable» and «steady», as a rule, are not considered synonyms in modern technical literature.

It is generally accepted that the steady process is a process that returns to the equilibrium state after any, rather small initial deviation caused by the effect of external disturbances. In welding, this notion is used to analyse of the so-called arc process self-regulation phenomenon.

Stability of a technological process usually means a property of the latter that provides constancy of the probability distribution for its parameters during a certain period of time without any interference from outside [10]. In other words, the process the deviation of parameters of which from the mean values does not exceed the specified level is called stable. Accordingly, the measure of stability of the process is deviation of its parameters from the mean values. Normally, the following variance is taken as a measure of deviation of a discrete signal from mean value $\bar{x}$:

$$\sigma^2(x) \approx \frac{1}{n-1} \sum_i^n (x_i - \bar{x})^2,$$

where n is the quantity of changes, or $\sigma(x) = \sqrt{\sigma^2(x)}$ is the standard deviation, or variation coefficient $K_V(x) = \sigma(x)/\bar{x})$.

Most often the welding process stability is considered to be stability of the arc and stability (regularity) of transfer of the electrode metal into the weld pool.

The set of the indicators used to characterise the welding process stability depends on the welding method and method of transfer of the electrode metal into the weld pool.

Manual covered-electrode welding. In the majority of cases only one indicator is used for this welding method — stable or unstable arc. Expert estimation of stability of the arc according to the three- [6] or four-point system is sometimes used, as recommended in GOST 25616–83 (ST SEV 3235–81) [1]. Independently of the kind of the welding current, the welding process stability is assessed by a test welder according to the frequency of extinctions of the arc, uniformity of its burning, vibration and sounding of the arc. The standard contains no clear definitions what exactly the uniformity of burning and vibration of the arc mean. Needless to say that inherently the expert estimates are subjective and require that experts be highly qualified.

In principle, visual and acoustic parameters of stability of the welding process mentioned in standard [1] can be fixed by using instruments and then mathematically processed to obtain quantitative estimates. Thus, sounding of the arc is determined with a microphone, and light emission — with a corresponding photodetector. Acoustic emission (sounding of the welding arc, the intensity and character of which is used to evaluate stability of the welding process) results from oscillations of the surface of the arc column. The intensity of sounding of the arc is proportional to the rate of oscillations of its power, i.e. the rate of variations in the arc current [11]. Variations in the light emission are determined by oscillations of the arc power as well. Therefore, the light and acoustic emissions of the arc as parameters of instability of the welding process are secondary with respect to the electric parameters, i.e. welding current I_w and arc voltage V_a. Naturally, for this reason it is better to use I_w and U_a for objective estimation of the arc stability, as they are easier to measure compared to the light and acoustic emissions. Instrumental determination of the arc extinctions from the voltage or current is not difficult either.

Manual AC covered-electrode welding. In AC welding, as value of the current falls to zero in each half-period of the mains voltage, this causes extinction of the arc, which again ignites after some time. Such natural extinctions of the arc do not always end with its repeated ignition in the next half-period of the supply voltage. As a result, AC welding is the most unstable process out of all welding processes, while frequency of the arc extinctions is, undoubtedly, the main objective indicator of its burning.

E.M. Kuzmak [12] was the first to offer using the frequency of extinctions of the arc to characterise stability of its burning. Later on, study [13] used the number of the arc extinctions per electrode length, N_{ext}, and study [14] used that per electrode unit length. No doubt, the relative number of the arc extinctions is a direct numeric parameter of stability of the arc burning at the alternating current.

In addition to the frequency of the arc extinctions, there are many indirect parameters suggested to characterise not the arc stability proper, but the probability of the repeated arc ignition. Mainly, these are the parameters that characterise residual plasma after extinction of the arc and electric characteristics of the welding circuit responsible for the repeated arc ignition.

G.I. Leskov suggested that stability of the arc for electrodes with different coverings should be estimated from the initial rate of growth of the current at its repeated ignition, di_2/dt [15]. The higher the value of this indicator, the more stable is considered to be the arc burning [7]. This indicator is determined from phase characteristic $di/dt = f(i)$.

As the rate of variations in the welding current when it passes through zero is determined, to a significant degree, by its effective value, to exclude the effect of the latter V.Yu. Arlauskas and I.R. Narushkevichyus [8] offered the following dimensionless indicator of stability of the arc ignition:

$$K_i = \frac{di_2/dt}{di_1/dt} 100\ \%,$$

where di_1/dt is the maximal rate of decay of the welding current before the arc extinction. According to this indicator, an ideal stability of the arc takes place at $K_i = 100$ %.

Not all researchers consider the use of these indicators efficient for evaluation of stabilising properties of welding consumables. For example, in the opinion of V.A. Troitsky [16], growth of the pre-arc and arc currents greatly depends on the linearity of a source, and the rate at which the current passes through zero is determined only by the electric characteristic of the welding source.

Another indicator of the arc stability in welding without short circuits is given in study [17]: $B_i = I_i/(U_i t_i)$, where U_i and I_i are the voltage at electrodes and current in the inter-electrode gap at the moment of recovery (ignition) of the arc discharge, and t_i is the time of interruption of the arc burning (ignition). The higher the value of this indicator, the more stable is considered to be the arc.

For manual arc welding without short circuits, I.I. Zaruba and V.V. Dymenko [18] offered the following indicator of the arc stability: $K_{st} = I_{cr}/\tau$, where I_{cr} is the critical arc current at the moment of extinction and passage of the electrode metal droplet through the arc, below which the arc may go out, and τ is the critical time during which the arc plasma will most likely be destroyed as a result of the metal transfer. Detachment of a droplet at the end of half-period of the welding current may lead to the point that the latter will disappear earlier than its value will naturally pass through zero, this being accompanied by increase in no-current time range t_i. In contrast to the previous stability indicators, K_{st} characterises the probability of the repeated ignition of the arc after its extinction and transfer of the electrode metal droplet.

Except for the frequency of the arc extinctions, strictly speaking, none of the offered indicators is an indicator of the arc stability or stability of the welding process as a whole. For the alternating current, its mean value is equal to zero. Therefore, standard deviation of the current is not an indicator of its stability, but a measure of its value, and is called the effective value of current I. In this case, variance $\sigma^2(I)$, standard deviation $\sigma(I)$ or coefficient of variation of the effective value of the welding current, K_V^I, can be used as an objective indicator of the welding process stability, according to the above definition of stability. Similarly, variance $\sigma^2(U)$, standard deviation $\sigma(U)$ or coefficient of variation of the effective value of voltage at electrodes, K_V^U, can be used as a stability indicator for the arc voltage drop. These parameters are indicators of the process stability only in welding without regular short circuits.

In manual arc welding, metal transfer takes place mostly with regular short circuits [15, 19]. Naturally, the presence of short circuits affects variations of the effective values of the welding current and arc voltage. Moreover, these variations may be higher or lower than the variations caused by the effect of other disturbances. Therefore, variations in the welding current and arc voltage are insufficiently sensitive to instability of the short circuits. Stability of the short circuits can be more efficiently evaluated from the standard deviation of their frequency $\sigma(f_{s.c})$ and duration $\sigma(\tau_{s.c})$. If welding parameters provide for the absence of regular short circuits, the instability of the process because of short circuits should be estimated from the value of $f_{s.c}$: the higher this value, the more stable is the welding process.

Manual DC covered-electrode welding. For the first time the quantitative estimation of the arc stability was suggested by K.K. Khrenov [6], who assessed stability of the arc from its length at extinction: the longer the arc at extinction for a fixed electrode, the smaller is the number of the arc extinctions during welding and, therefore, the more stable is the arc. This method has a drawback consisting in the errors caused by the effect of the droplets that had no time to detach from the electrode tip before the arc extinction. The method gives a scatter of 15–30 % [7]. Strictly speaking, the length of the arc at extinction is a measure of its elasticity, which is singled out as a separate indicator of quality of the arc [1], and is only indirectly related to the frequency of the latter. Different authors use different statistical parameters of the welding current and arc voltage as a measure of uniformity of arcing to estimate the arc stability.

For instance, V.M. Yazovskikh and co-authors suggested using variance $\sigma^2(I_w)$ [20], standard deviation $\sigma(I_w)$ or welding current variation coefficient $K_V^{I_w}$ [21, 22] as stability indicators. The authors are of the opinion that the lower the value of these parameters, the more stable is the arc.

Study [5] checked the possibility of estimation of the arc stability from $\sigma^2(U_a)$. It is the opinion of the authors that this indicator does not correlate with the arc stability in DC covered-electrode welding.

Mechanised DC gas-shielded arc welding. Most publications relate to stability of welding with short circuits, as the welding process with a spray metal transfer is stable in its nature, and that with a drop metal transfer is unstable. In this connection, the trend is not to apply the last welding method.

In CO_2 or gas mixture shielded short-arc welding the molten metal is transferred from the electrode into the weld pool in short circuiting of the arc gap. As a result, the instantaneous values of the welding current and arc voltage periodically vary over wide ranges. Numerous investigations were carried out to study the welding current and arc voltage to identify the indicators reflecting the welding process stability. For this, the primary consideration was given to statistical parameters of the welding current and arc voltage. The list of these parameters that is far from being complete is given in Table 1.

It is thought that the lower the value of any of these parameters, the more stable is the welding process. However, this is not always true for some of the parameters.

In metal-electrode short-arc welding with periodic short circuits of the arc gap, pulse welding or modulated current welding the arc voltage and welding current are inherently of a pulse character, i.e. they periodically change their values. In definition, any periodically changing (modulated) signal has values of σ^2, σ and K_V other than zero. To illustrate, Figure 1, *b* and *c* shows results of modelling of the welding current and arc voltage in metal-electrode welding with periodic short circuits (Figure 1, *a*). Modelling was performed for open-circuit voltage $E1$ = 20 V, voltage $E2$ = 12 V that depends on the near-electrode voltage drop and arc length, internal active resistance $R1$ = 0.05 Ohm of the power supply and welding circuit, electrode extension resistance $R2$ = 0.05 Ohm, arc column resistance R_a = 0.025 Ohm, and τ = 20 ms.

Figure 2 shows dependence of $K_V^{I_w}$ and $K_V^{U_a}$ on duty factor $D = \tau_{s.c}/\tau$ and inductance L of choke of the device (see Figure 1, *a*). The curves are given for an ideally stable process of transfer of the molten metal into the weld pool at a constant frequency of short circuits. It can be seen from Figure 2 that even with the ideally stable process, $K_V^{I_w}$ and $K_V^{U_a}$ have rather high values, which vary over wide ranges depending on the parameters of the welding circuit and welding conditions. Naturally, instability of the welding process, i.e. random variations in the short circuit frequency, short circuit time, arc length and other parameters, leads to increase in the variation coefficient, compared to the ideally stable welding process. But their effect on $K_V^{I_w}$ and especially on $K_V^{U_a}$ is insignificant. As an example, below we give values of $\sigma(U)$ for rectangular pulses of unit amplitude of U_{max} and duty factor $D = t_p/T$ = 0.7 at random variations in pulse amplitude T and pulse duration τ_p. The normal distribution law with standard deviations of $\sigma(U_{max})$ and $\sigma(t_p)$ is accepted for the pulse amplitude and duration.

As seen from the below data, instability of the arcing time has almost no effect on $\sigma(U)$:

Table 1. Published data on indicators of stability of arc welding processes

Parameter of welding process stability	Welding method with short circuits	Reference
$\sigma^2(U_a)$	In CO_2	[23]
$\sigma(U_a)$	Same	[24]
$K_V^{U_a}$	»	[3, 25]
$C_V^{U_a}$	»	[25]
$\sigma(I_w)$	»	[24]
$K_V^{I_w}$	»	[3, 25]
$C_V^{I_w}$	»	[25]
$\sigma(I_{max})$	In CO_2, in gas mixtures	[26, 27]
$\sigma(I_{min})$	In gas mixtures	[28]
$K_V^{I_{max}}$	In CO_2	[2, 29]
$\sigma^2(\tau_{s.c})$	Same	[23]
$\sigma(\tau_{s.c})$	Same In CO_2, in gas mixtures	[24] [27]
$K_V^{\tau_{s.c}}$	In CO_2 In gas mixtures	[3, 30] [31]
$\sigma^2(\tau_a)$	In CO_2	[23]
$\sigma(\tau_a)$	Same In gas mixtures	[24] [27]
$K_V^{\tau_a}$	In CO_2 In gas mixtures	[30] [31]
$\sigma^2(f_{s.c})$	In CO_2	[32]
$N_{s.c}^r$	In gas mixtures	[31]
$\sigma(\tau)$	In CO_2, in gas mixtures In gas mixtures without short circuits	[26, 27, 33] [34]
$\sigma(U_a^a)$	With short arc in CO_2	[23]
$\sigma(U_a^{s.c})$	Same	[23]
$\overline{\tau}_{s.c}$	In CO_2	[3]
$K_V^{\tau_{ext}}$	Same	[30]
$(I_w - U_a)$ diagram	In gas mixtures without short circuits	[31]
9th and 10th quantiles of density of distribution of U_a	Same	[24]
9th and 10th quantiles of density of distribution of I_w	»	[24]

Note. $C_V^{U_a} = K_V^{U_a}/f_{s.c}$ — coefficient of variation of welding voltage related to short circuit frequency; I_{max} — amplitude of short-circuit current; $C_V^{I_w} = K_V^{I_w}/f_{s.c}$ — coefficient of variation of welding current related to short circuit frequency; $\tau_{s.c}$ — duration of effective short circuit; $\overline{\tau}_{s.c}$ — average duration of all short circuits; τ_a — duration of arcing between short circuits; τ — standard deviation of short circuit duration; $\tau = \tau_{s.c} + \tau_a = 1/f_{s.c}$; $N_{s.c}^r = n_{s.c}^r/n_{s.c}^0$ — relative number of random short-time (with duration of less than 1.5 ms) short circuits, i.e. short circuits at which no metal transfers to the weld pool; $n_{s.c}^r$ — number of random short circuits; $n_{s.c}^0$ — total number of short circuits; U_a^a — voltage in the arcing phase; $U_a^{s.c}$ — voltage during a short circuit; $K_V^{\tau_{ext}} = \sigma(\tau_{ext})/\tau_{ext}$ — coefficient of variation of arc extinction duration τ_{ext}.

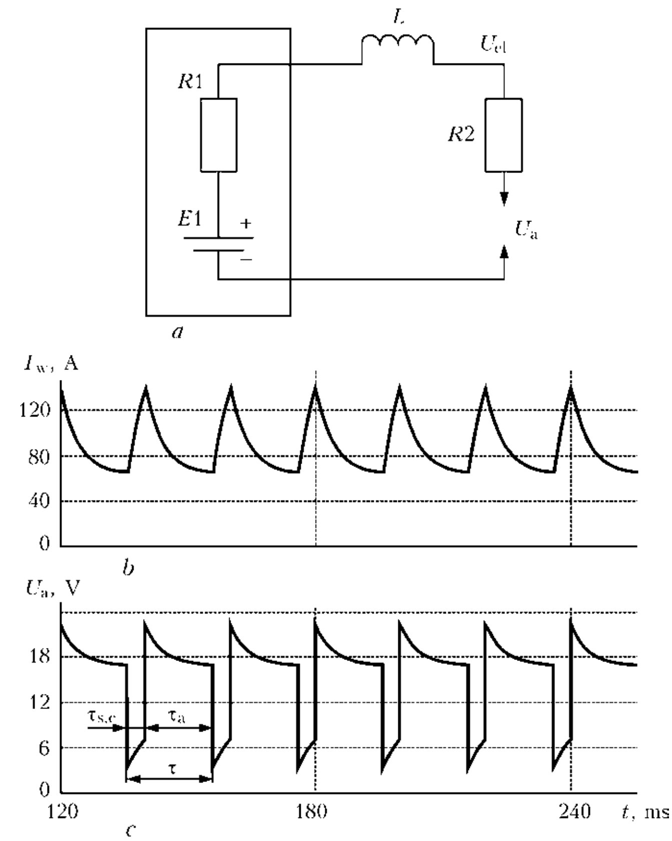


Figure 1. Equivalent circuit of power supply with a welding circuit (*a*), and oscillograms of welding current I_w (*b*) and arc voltage U_a (*c*) ($U_a = E_a + R_aI_w$)

$\sigma(t_p)$	0	0.05	0.10	0.15	0.20
$\sigma(U)$	0.25099	0.25106	0.25111	0.25118	0.25124

In oscillations of the pulse amplitude, variance $\sigma^2(U_{max})$ is summed up with variance $\sigma_0^2(U)$ caused only by short circuits ($\sigma^2(U_{max}) = 0$):

$\sigma(t_{max})$	0	0.05	0.10	0.15	0.20
$\sigma(U)$	0.25099	0.25477	0.26527	0.28172	0.30316

Therefore, in welding with periodic short circuits, pulse welding and modulated-current welding the values of σ^2, σ and K_V of the welding current (voltage) characterise mostly the shape and parameters of modulation of the welding current (voltage) and, to a lesser degree, stability of the welding process.

The above drawbacks of $\sigma(U_a)$ will not take place, providing that the standard deviations of voltage only during the short circuits, $\sigma(U_a^{s.c})$, and arcing, $\sigma(U_a^a)$, are used separately [24].

In welding without regular short circuits, σ^2, σ and K_V are, by definition, the indicators of the welding process stability reflecting in addition such instabilities as arc extinctions and short circuits. However, if these disturbances are relatively infrequent, then, as follows from Figure 2, they will have a low effect on σ^2, σ and K_V. In this case, it is more expedient to directly measure short circuit frequency $f_{s.c}$ and arc extinctions f_{ext} as the stability indicators.

It should be borne in mind that the accuracy of estimation of the process stability in welding without short circuits from the values of σ^2, σ and K_V decreases because of interferences caused by pulsations of voltage of the welding power supply. In six-phase bridge rectifiers that are characteristic of the thyristorised welding power supplies, the ratio of the effective value of fundamental harmonic (300 Hz) to the mean value of rectified open-circuit voltage may vary from 0.05 to 0.37, depending on the switching angle of the thyristors [35]. In this case, an efficient means for improving the accuracy of estimation of parameters of the welding process stability is filtering of these interferences, as the frequency of variations in the welding current and voltage caused by instability of the welding process proper is rarely in excess of 200 Hz.

Study [31] suggests that the I_w–U_a diagram should be analysed to identify such instabilities of the welding process in gas mixtures as random short-time short circuits, abnormal increase in voltage during repeated ignition of the arc after a short circuit, and arcing between the short circuits.

Standing apart is another, rather exotic stability indicator suggested in study [24]. It is a difference between the 9th and 10th quantiles of density of distribution of the arc voltage and welding current. The lower the values of these quantiles, the higher is the stability of the gas mixture-shielded welding process with short circuits.

As follows from Table 1, the most popular indicators for estimation of stability of the welding process with short circuits are stability parameters $f_{s.c}$ and $\tau_{s.c}$. It can be shown that these parameters reflect stability of transfer of the electrode metal into the weld pool. In fact, the stable GMAW process is characterised by an unfailing observance of the equality of a mean volume electrode melting rate and volume electrode feed rate:

$$\overline{v}_f S_{el} = f_{s.c} Q_d,$$

where $\overline{v}_f$ is the linear rate of feed of the electrode wire; S_{el} is the electrode cross section area, and Q_d is the volume of a droplet. If distributions of variables $\overline{f}_f$, S_{el} and Q_d are normal, and their standard deviations are independent, based on the above formula it can be written down for the short circuit frequency standard deviation that

$$\sigma(f_{s.c}) = \sqrt{\left(\frac{S_{el}}{Q_d}\right)^2 \sigma^2(v_f) + \left(\frac{v_f}{Q_d}\right)^2 \sigma^2(S_{el}) + \left(\frac{v_f S_{el}}{Q_d^2}\right)^2 \sigma^2(Q_d)}.$$

It can be seen from this dependence that $\sigma(f_{s.c})$ directly characterises instability of the electrode wire feed rate, wire cross section area and droplet volume. As instability of the first two parameters is not high, $\sigma(f_{s.c})$ is mainly a measure of instability of the droplet volume.

As $f_{s.c} = 1/(\tau_{s.c} + \tau_a)$, similar dependencies can also be derived for $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$:

$$\sigma^2(\tau_{s.c}) + \sigma^2(\tau_a) = \left(\frac{1}{v_f S_{el}}\right)^2 \sigma^2(Q_d) + \left(\frac{Q_d}{v_f^2 S_{el}}\right)^2 \sigma^2(v_f) + \left(\frac{Q_d}{v_f S_{el}^2}\right)^2 \sigma^2(S_{el}).$$

As a characteristic of instability of $\overline{v}_f$, S_{el} and Q_d, this formula has no advantages over the previous one. Hence, it is enough to estimate only $\sigma(f_{s.c})$. However, it is absolutely obvious that, in addition to instability of the droplet volume, $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$provide information on fluctuations of other parameters of the welding process as well. For example, $\sigma(\tau_{s.c})$ depends on the instability of shape of the droplet, variations in its position on the electrode tip, instability of shape of the short circuit current, oscillations of the weld pool surface, etc. In turn, the $\sigma(\tau_a)$ values depend on variations in the electrode extension, oscillations of the welding current and arc voltage drop, volume of the molten metal remaining on the electrode tip in repeated ignition of the arc after a short circuit, etc. Therefore, collectively $\sigma(\tau_{s.c})$ and $\sigma(\tau_a)$ provide a more comprehensive characterisation of stability of the welding process with short circuits than only $\sigma(f_{s.c})$.

Table 2 gives parameters of stability of the GMAW process recommended on the basis of the above-said. The lower the value of the given parameters, the higher is the stability of the welding process. All of the above indicators of the welding process stability can be determined by processing only the arc voltage and welding current values.

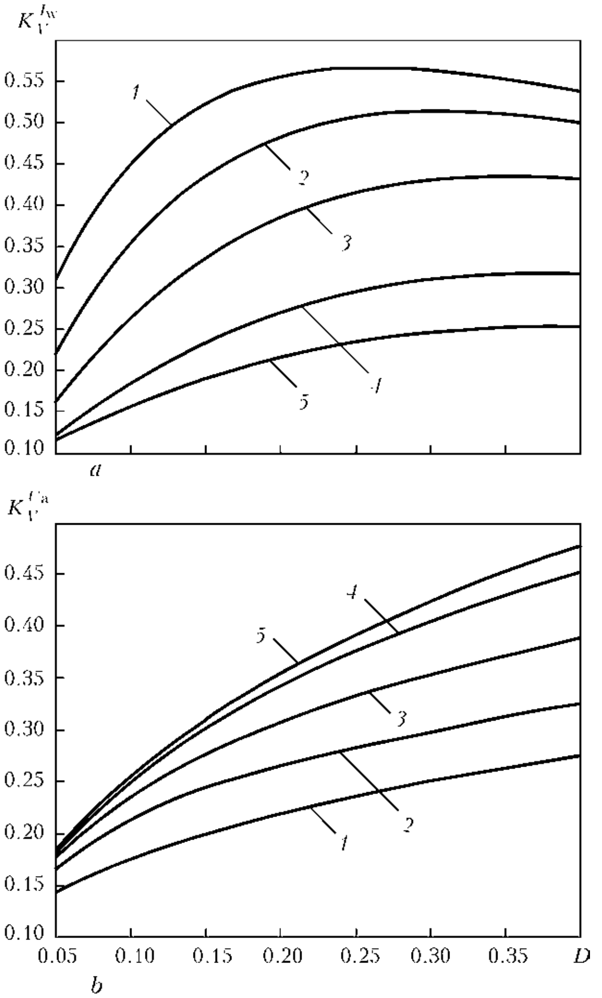


Figure 2. Dependence of coefficients of variations of welding current $K_V^{I_w}$ (*a*) and arc voltage $K_V^{U_a}$ (*b*) on duty factor *D* at different values of the device choke inductance (see Figure 1, *a*): *1* — *L* = 0.050; *2* — 0.125; *3* — 0.250; *4* — 0.500; *5* — 0.750 mH

Pulse welding and modulated current welding. The following parameters in different combinations, depending on the mode of operation of the welding power supply (stabilisation of current or voltage), can serve as indicators of the process stability for the above welding methods: $K_V^{I_p}$, $K_V^{I_b}$, $K_V^{U_p}$ and $K_V^{U_b}$, where I_p is the pulse current; I_b is the base current; U_p is the pulse voltage, and U_b is the base voltage.

As stability of the welding process is characterised by several indicators, this makes it necessary to form one integrated indicator (objective function) from them by using the significance coefficient for each indicator.

The following functional dependence is used for this: $\gamma = f(n, b_i, k_i)$, $i = 1, 2, 3, \ldots, n$, where n is the quantity of the accountable unit indicators; b_i is the coefficient of significance of the i-th indicator, and k_i is the i-th indicator.

Table 2. Recommended parameters of stability of the GMAW process

Welding process stability parameter	Manual welding			Automatic and mechanised gas-shielded welding	
	Alternating current	Direct current			
		With short circuits	Without short circuits	With short circuits	Without short circuits
N_{ext}	+	–	–	–	–
$f_{s.c}$	–	–	+	–	+
$f^{f}_{s.c}$	–	+	–	+	–
$\sigma^2(I) \vee \sigma(I) \vee K_V^I$	+	–	–	–	–
$\sigma^2(U) \vee \sigma(U) \vee K_V^{U_a}$	+	–	–	–	–
$\sigma^2(I_w) \vee \sigma(I_w) \vee K_V^{I_w}$	–	–	+	–	+
$\sigma^2(U_a) \vee \sigma(U_a) \vee K_V^{U_a}$	–	–	+	–	+
$\sigma^2(I_w^{s.c}) \vee \sigma(I_w^{s.c}) \vee K_V^{I_w^{s.c}}$	–	+	–	+	–
$\sigma^2(I_w^a) \vee \sigma(I_w^a) \vee K_V^{I_w^a}$	–	+	–	+	–
$\sigma^2(U_a^{s.c}) \vee \sigma(U_a^{s.c}) \vee K_V^{U_a^{s.c}}$	–	+	–	+	–
$\sigma^2(U_a^a) \vee \sigma(U_a^a) \vee K_V^{U_a^a}$	–	+	–	+	–
$\sigma^2(f_{s.c}) \vee \sigma(f_{s.c}) \vee K_V^{f_{s.c}}$	–	+	–	+	–
$\sigma^2(\tau_{s.c}) \vee \sigma(\tau_{s.c}) \vee K_V^{\tau_{s.c}}$	–	+	–	+	–
$\sigma^2(\tau_a) \vee \sigma(\tau_a) \vee K_V^{\tau_a}$	–	+	–	+	–

Note. 1. $f^{f}_{s.c}$ — frequency of false short circuits. 2. Sign + shows applicability, and sign — shows inapplicability of parameter depending on the welding method and type of transfer of the electrode metal into the weld pool.

Function of the type of $\gamma = \sum_i^n b_i k_i$ is normally used, and function $\gamma = \prod_i^n k_i^{b_i}$ is used very rarely. An important element of formation of the integrated indicator is setting of the values of the significance coefficients. Dozens of methods for determining them are available [36, 37], the most common one among them being an expert estimation of the significance coefficients.

Only one integrated indicator has been suggested so far to characterise stability of the welding process (CO_2 welding with short circuits) [30]:

$$\gamma = k_0 K_V^{\tau_{exp}} + k_1 K_V^{\tau_{s.c}} + k_2 K_V^{\tau_a},$$

where k_0 is the relative total time of the arc extinctions; and k_1 and k_2 are the relative total times of the short circuits and arcing, respectively.

The minimal value of coefficient γ corresponds to the maximum stable welding process. It should be noted that this integrated stability indicator allows for the arc extinctions that take place mostly in the beginning of welding at excitation of the arc. Standard [1] sets off reliability of establishing of the welding process (initial arc ignition) as a separate indicator of welding properties of the power supplies, which is not related to indicators of the welding process stability. In addition, the choice of k_0, k_1 and k_2 as the significance coefficients should not be considered the only possible one.

Study [38] offers a simple integrated parameter of the welding process stability:

$$PR = \frac{I_{bk} U_{bk}}{I_{mean} U_{mean}},$$

where I_{mean} and U_{mean} are the mean values of the welding current and arc voltage; U_{bk} is the arithmetic mean of digitised value of the arc voltage lower than U_{mean} within the measurement range, and I_{bk} is the arithmetic mean of digitised value of the welding current lower than I_{mean}.

To provide the stable process, it is required that $0.2 < PR < 0.4$ (process with short circuits), $0.8 < PR < 0.9$ (drop metal transfer) and $0.95 < PR < 0.98$ (spray metal transfer). In the intermediate zones the welding process is unstable and characterised by increased spattering.

Also, the above study offers the stability criteria in the form of a set of rules based on the following three dimensionless parameters:

$$TI = 1 - \frac{I_{min}}{I_{mean}}, \quad TSI = \frac{I_{max}}{I_{mean}}, \quad DCI = 1 - \frac{U_{bk}}{U_{mean}},$$

where I_{max} and I_{min} are the maximal and minimal values of the welding current, respectively. These rules are formulated as follows:

• the welding process is stable if (($TI < 0.1$) and ($DCI < 0.1$) and ($TSI < 1.1$)), or (($0.3 < TI < 0.5$) and ($0.5 < DCI < 0.8$) and ($TSI < 0.2$);

• the welding process is stable enough if ($0.3 < TI < 0.5$) and ($0.3 < DCI < 0.5$) and ($TSI < 0.2$).

All numerical values of limits of the given parameters were obtained as a result of processing of expert estimates made by associates of the Crandfield University (Great Britain).

CONCLUSION

The welding process is called stable if deviation of its parameters from the mean values is not in excess of the specified level. The measure of stability of the welding process is deviation of its parameters from the mean values. The variance of a parameter, standard deviation or variation coefficient is taken as its deviation from the mean value.

The simplest way of evaluating stability of the GMAW process is to evaluate stability of its electric parameters. It is inexpedient to use variance, standard deviation or coefficient of variation of the welding current and arc voltage to evaluate stability of the process of pulse welding, modulated current welding and welding with metal transfer at periodic short circuits of the arc gap.

The set of indicators of the welding process stability depends on the welding method and character of transfer of the electrode metal into the weld pool. The set of the indicators of the welding process stability can be combined into one integrated stability indicator, allowing for the significance coefficient.

Stability of the welding process also depends on the welding consumables, welding equipment and welding parameters.

Therefore, based on ensuring the process stability, it is necessary to compare, e.g. welding consumables by using the same equipment and the same welding parameters. When investigating dependence of stability of the welding process on the welding equipment and parameters, it is necessary to keep to the similar conditions.

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PROPERTIES AND STRUCTURE OF CIRCUMFERENTIAL JOINTS OF TUBES MADE BY ORBITAL ELECTRON BEAM WELDING

E.G. TERNOVOJ, V.F. SHULYM, A.R. BULATSEV, T.G. SOLOMIJCHUK and **V.A. KOSTIN**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The paper presents investigations of the properties and structure of metal in circumferential joints of tubes from 304SS steel, PT-3V titanium alloy and monel alloy, produced by the method of orbital electron beam welding in vacuum. Performed investigations were focused on application of equipment and technology of orbital electron beam welding for repair of piping located outside functioning space objects.

Keywords: *piping, position butts, orbital electron beam welding, joints, 304SS steel, PT-3V titanium alloy, monel alloy, mechanical properties, macro- and microstructures, microhardness, chemical inhomogeneity*

Problem of welding position butts of various purpose piping is urgent for performance of repair operations on board the International Space Station (ISS) in space. Analysis of long-term operation of space facilities under the conditions of an orbital flight, in particular, of Russian orbital complex «Mir» reveals that one of the most vulnerable elements is technological piping which can fail during long-term operation for various reasons (mechanical damage, impact of meteorite particles, etc.) and can require repair under the conditions of space [1–4]. One part of the piping is inside the functioning modules, the other is located outside the station and is operating in the space vacuum at below zero temperatures. It is anticipated that after 6–10 years since the beginning of ISS operation a need may arise for their repair and for processes and devices for its implementation, accordingly.

Many years of research conducted at PWI demonstrated that the most acceptable method for repair of piping located inside the space modules, is TIG welding process in specialized put-on chambers with a controllable atmosphere [5–8], and for repairs outside the station this is electron beam welding [3, 4, 8].

TIG welding is usually used to weld butt joints with filler material feed or over flanges. Overlap joints, as well as circumferential joints of tubes made by multipass autopressing method, are welded without filler material, their strength being not lower than that of joints welded with feeding of filler wire of matching composition [9–13].

In EBW of circumferential joints in one pass (without edge flanging) a depression forms on the weld face that essentially lowers the joint mechanical properties. In this connection, it is of interest to produce a sound butt joint of tubes by EBW process without feeding filler material and with reinforcement of the weld root and top part.

This paper gives the results of studying the properties and structure of tube joints made at retrofitting the technology of single- and two-pass orbital EBW without addition of filler materials, to produce vacuum-tight, strong and sound welded joints in order to solve the problems of pipeline repair in open space.

Experiments were performed using a laboratory power unit with electron beam heater that was rotating around a stationary tube (Figure 1). Samples were butt welded in a single pass or two passes, without addition of filler materials. Tubes of 12.8 mm diameter with 1.0 mm wall thickness from stainless steel 304SS, PT-3V titanium alloy and NMZhMts nickel alloy (monel) were used as samples. Optimum modes of orbital EBW, properties and structural features of the produced welded joints of tubes were determined.

Quality of the produced joints was assessed by external examination, checking the vacuum tightness of the joints with helium leak detector TI-1-14; rupture testing of tubes in TsDM-10 machine at the temperature of +20 °C, and in IMP machine at −196 °C temperature; flattening tests for ductility to GOST 8695–75 in TsDM-10 machine; investigations of macro- and microsections of the joints. Composition of base metal and weld metal was determined by spectral analysis using photoelectric spectrometer DFS-36.

Metallographic examination of the geometry and metal structure both of the entire joint and its individual sections was conducted in «Neophot-32» optical microscope. Joint microhardness $HV1.0$ MPa was measured on longitudinal sections of tubes in the LECO microhardness meter M-400 with 200 μm step. Structural components of 304SS steel were revealed by electrochemical etching in 20 % water solution of chromic acid at 10 V voltage for 5 s, and components of titanium alloy PT-3V were revealed by chemical etching in a reagent of the following composition: 1 volume fraction of HF; 3 volume fractions of HNO_3, 6 volume fractions of H_2O. Structure of monel alloy was revealed by electrochemical etching in 20 % water solution of ammonia sulphate at 20 V voltage for 5 s.

Table 1. Modes of orbital EBW for circumferential butt joints of tubes of ∅12.8 × 1.0 mm

#	Material	I_b, mA	U, kV	v_w, m/h	t_1, s	t_2, s	t_3, s
1	304SS	35.0	9.2	22	0.5	14.0	3.0
2	PT-3V	32.5	9.5	36	1.5	8.0	3.5
3	Monel	35.0	9.2	15	1.0	16.0	3.0

Note. t_1 — time for reaching working parameters; t_2 — time of welding at working parameters; t_3 — time of fading out.

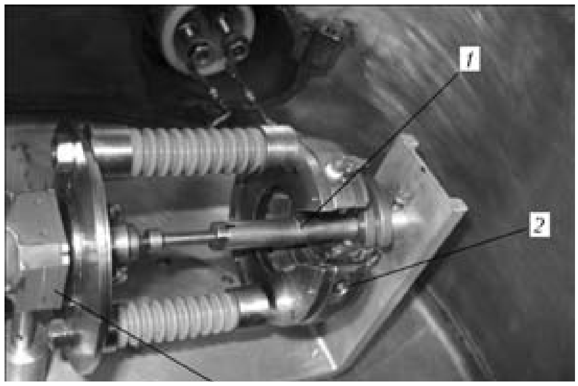

Figure 1. Test sample of electron beam heater for orbital EBW of butt joints of tubes: *1* — welded sample; *2* — circular electron beam heater; *3* — orbital revolution drive

Quantity of δ-ferrite in the weld metal and base metal of welded joints was determined by ferritometer Ferrit Gehaltmesser-1.053. Chemical inhomogeneity of base metal and weld metal was studied in the Cameca microanalyzer SX-50.

Conducted experiments enabled determination of optimum modes of orbital EBW of circumferential joints of tubes from steel 304SS, titanium alloy PT-3V and monel alloy at up to 400 W beam power. Accelerating voltage, beam current, welding speed and time intervals of welding cycle were selected depending on tube material. Here accelerating voltage, beam current and welding speed are identical both for single- and two-pass welding. Welding mode parameters are given in Table 1.

Analysis of macrosections of tubes from 304SS steel, PT-3V alloy and monel alloy (Figure 2) showed that selection of welding modes enables achievement of optimum geometry and satisfactory formation of the upper and root reinforcement beads without addition of filler materials. Checking of welded joints for vacuum tightness did not reveal any violation of tightness of welds made with different number of passes.

It should be also noted that the composition of weld metal in joints of the above materials does not differ from initial composition of base metal (Table 2), and is independent on the number of passes.

Obtained results of rupture testing of single-pass joints (Table 3) of tubes from steel 304SS at testing temperatures of +20 °C were equal to (0.74–0.77)$\sigma_t^{b.m}$, and for sample welded in two passes it was 0.95$\sigma_t^{b.m}$. At testing temperatures of −196 °C these values increased by 10–15 % both for base metal and for welded joints compared to values obtained at +20 °C temperature. Strength values of joints from monel alloy are similar to those of joints from 304SS steel. For titanium alloy PT-3V rupture testing was performed only at the temperature of +20 °C. Having analyzed the results of the conducted testing, it should be noted that the highest strength values were found in two-pass joints that did not have any depressions of the weld upper bead.

During flattening tests of welded joints and base metal no cracks were found on samples from 304SS steel and monel alloy, whereas on samples from titanium alloy PT-3V longitudinal cracks were detected in base metal tubes and welded joints (Figure 3).

Figure 2. Macrosections (×20) of butt welded joints produced by orbital EBW in two passes: *a* — steel 304SS; *b* — titanium alloy PT-3V; *c* — monel alloy

Table 2. Composition (wt.%) and values of tensile strength of the studied alloys

Material	C	Mn	Cr	Ni	Si	P	Cu	Fe	Al	V	Mo	Zr	Ti	σ_t, MPa
304SS	0.2	2.0	18–20	8.0–10.5	1.0	0.045	–	Base	–	–	–	–	–	800
PT-3V	–	0.04	≤0.1	–	0.07	–	–	0.5	3.6	2.4	≤0.3	0.05	Base	810
Monel	–	1.2	–	Base	<0.2	–	30.5	2.0	–	–	–	–	–	680

Table 3. Values of tensile strength of circumferential joints of tubes produced by orbital EBW

Studied section	Material	Number of passes	σ_t, MPa, at T, °C		Fracture site
			+20	−196	
Base metal	304SS	–	798	923	BM
Welded butt joint		1	620	812	WM
		2	760	915	HAZ
Base metal	PT-3V	–	800	–	BM
Welded butt joint		1	460	–	WM
		2	712	–	HAZ
Base metal	Monel	–	670	780	BM
Welded butt joint		1	560	680	WM
		2	630	740	FZ

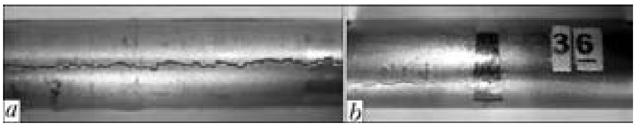

Figure 3. Samples of welded joint of titanium alloy PT-3V after flattening tests: *a* — base metal; *b* — orbital two-pass welding

Fracture of base metal samples of PT-3V alloy (in the form of cracks from both sides) occurred along the entire length of its generatrix. In welded samples cracks initiated also from both sides on the end faces and stopped on the boundary of base metal and HAZ. The weld and HAZ on both sides of the weld turned out to be so ductile that they acted as crack arresters (Figure 3, *b*). This is attributable to the fact that in

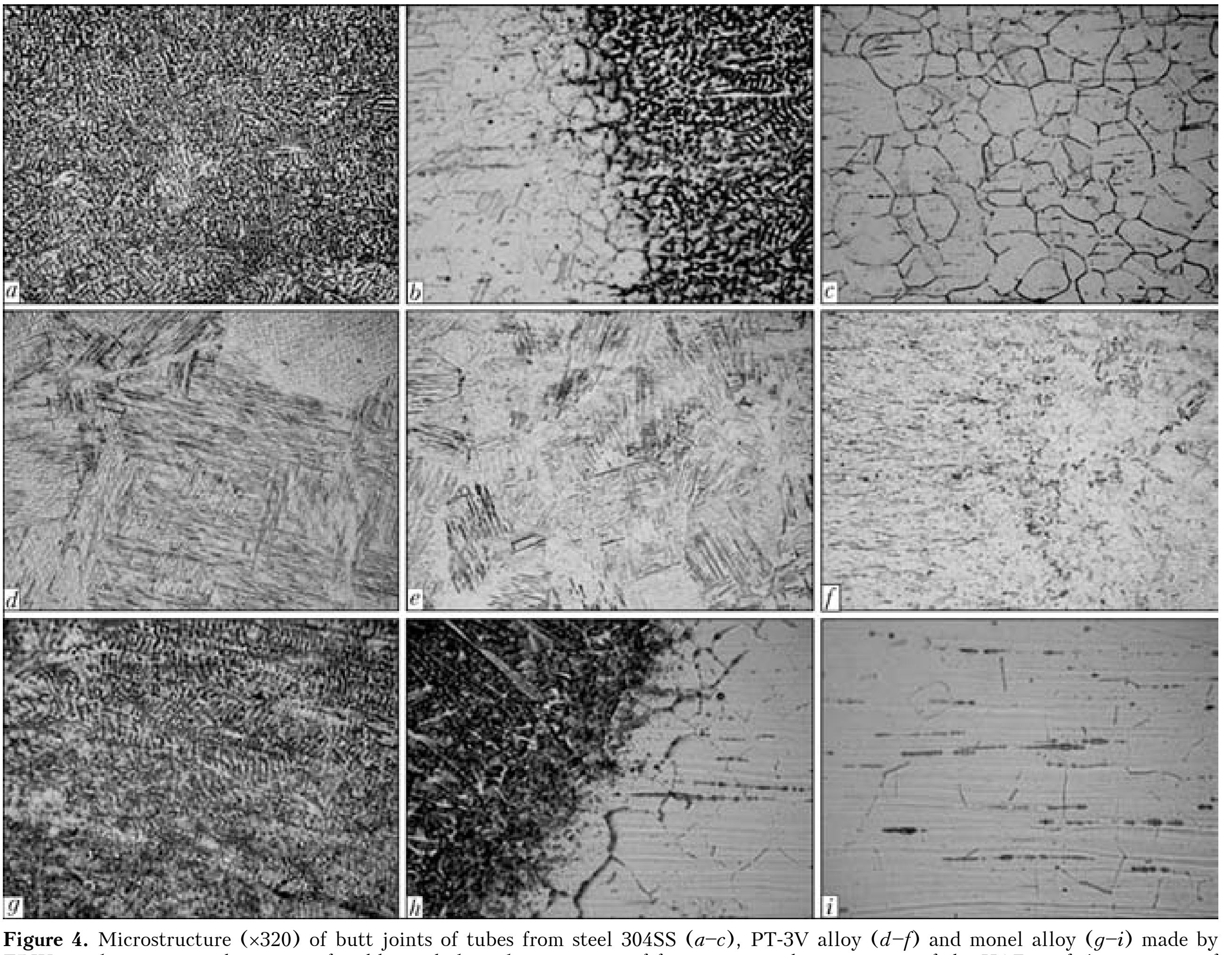

Figure 4. Microstructure (×320) of butt joints of tubes from steel 304SS (*a*–*c*), PT-3V alloy (*d*–*f*) and monel alloy (*g*–*i*) made by EBW: *a*, *d*, *g* — central sections of weld metal; *b*, *e*, *h* — sections of fusion zone and coarse grain of the HAZ; *c*, *f*, *i* — regions of HAZ and base metal boundary

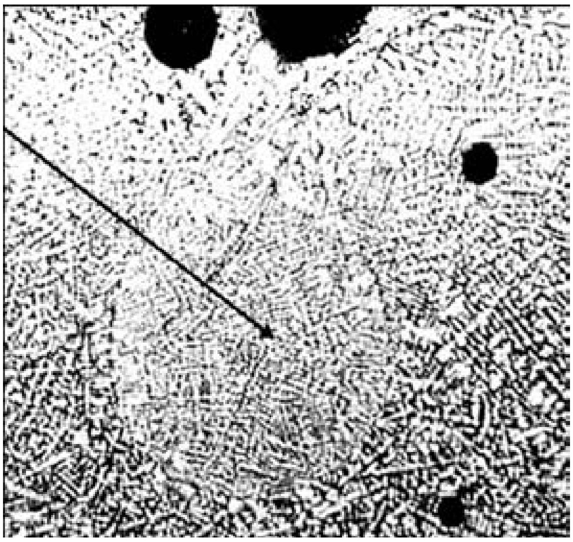

Figure 5. Microstructure (×320) of weld metal of a joint from monel alloy with porosity and a void, filled with solidified liquid metal after welding (along the arrow)

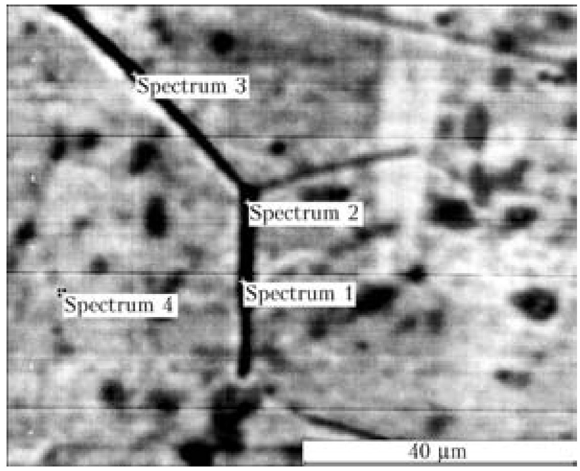

Figure 6. Interlayers along the grain boundaries in coarse grain zone (at the fusion line)

welding with this process the HAZ is more ductile compared to the tube base metal to which no thermal impact was applied.

Investigations of polished sections of joints from steel 304SS, titanium alloy PT-3V and monel alloy showed that such nonmetallic inclusions as oxides, sulphides, silicates, etc. were found in the base metal of steel 304SS and monel alloy, whereas practically no nonmetallic inclusions were present in titanium alloy PT-3V.

Microstructure of base metal and weld metal from 304SS steel (Figure 4, *a*–*c*) is mostly austenitic with a small quantity of δ-ferrite. Base metal of titanium alloy PT-3V (Figure 4, *f*) consists of grains of α-phase, elongated along the rolling stock texture, and that of weld metal and HAZ consists of grains of α′-phase (Figure 4, *d*, *e*). Microstructures of joints from PT-3V alloy have no clearcut fusion line (Figure 4, *e*). This promotes an improvement of ductility of HAZ section and inhibits crack propagation from the base metal into the HAZ and the weld (Figure 3, *b*). A clearcut boundary between the HAZ and base metal is also observed (Figure 4, *f*). Microstructure of base metal and weld metal of monel joints is similar to that of pure nickel [14] and has a single-phase composition of nickel-based solid solution (Figure 4, *g*, *i*). Small additives of iron and silicon, as well as copper but in larger quantities, are present in the solution and form no separate phases.

When studying the macro- and microstructures of welded joints of monel alloy produced by orbital EBW in a single pass, the weld metal demonstrated coarse and fine porosity (Figure 5). In addition, oval voids filled with metal with solidified submicrostructure are also observed (along the arrow). No such defects were found in welds made in two passes.

Formation of pores and cavities in joints from monel alloy is attributable to proneness of nickel and its alloys to formation of porosity in welding [15], as well as to a feature of hydrodynamic processes of liquid metal transfer in a narrow weld pool.

On the other hand, investigation of microstructure of HAZ metal from the fusion line to the boundary with the base metal in monel alloy joints also allowed revealing the presence of dark interlayers along the grain boundaries both in the HAS metal and in the base metal, which is not observed in the weld metal (see Figure 4, *g*–*i*).

Composition of these interlayers was studied in a scanning electron microscope JSM-35CF (JEOL, Japan), fitted with energy-dispersion microanalyzer system INCA 350. Analysis of electronographs confirmed the presence of dark interlayers along the grain boundaries (Figure 6), the composition of which was determined using INCA 350 microanalyzer.

Table 4. Distribution of microhardness of tube welded joints produced by orbital EBW, MPa

#	Material	Number of passes	Base metal	HAZ			Weld	
				Recrystallized zone	Double recrystallized zone	Overheated zone	Fusion zone	Weld middle
1	304SS	1	3060	2920	2500	2130	2380	2430
2		2	2980	2530	2300	2050	2300	2430
3	PT-3V	1	2740	2480	2350	2300	2300	2740
4		2	2700	2390	2300	2200	2300	2700
5	Monel	1	1700	1650	1600	1550	1600	1740
6		2	1620	1600	1580	1550	1540	1580

Obtained results of examination of these areas are indicative of an increased content of oxygen (up to 2.0 %), as well as aluminium (up to 0.4 %) and titanium (up to 0.2 %) compared to their content in the grain body. Apparently, predominant oxidation with formation of Al_2O_3 and TiO_2 oxides runs along the grain boundaries. Presence of oxides along the grain boundaries can promote an increase of stress intensity in these regions, that under certain conditions may lead to fracture propagation through them, which is a possible reason for the obtained results of rupture testing of tubular joints from monel alloy (Table 3).

Results of metallographic investigations are in good agreement with the results of rupture tests. Welds made in two passes have less nonmetallic inclusions and pores compared to single-pass welds and higher strength values, respectively.

Microhardness of the produced joints in the regions of weld metal, HAZ and in the base metal has different values, depending on the material and pass number (Table 4). For the studied materials microhardness after the second pass is more stable, but in the coarse grain section near the fusion line it is somewhat lower than after the first pass.

Investigations of chemical inhomogeneity by X-ray microprobe analysis showed that the uniform and equal distribution of alloying elements in welded joints from steel 304SS, titanium alloy PT-3V and monel alloy is independent on the number of passes.

Thus, orbital EBW process allows producing sound welded joints of tubes from stainless steels, monel alloy and titanium alloys.

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ELECTRON BEAM WELDING OF HEAT EXCHANGERS WITH SINGLE OR DOUBLE REFRACTION OF THE ELECTRON BEAM

L.A. KRAVCHUK, V.I. ZAGORNIKOV and **I.A. KULESHOV**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Selection of energy and time parameters of the electron beam in EBW of tubes to tubesheets of heat exchangers from titanium and the possibility of making a circumferential weld by applying single and double refraction are considered, as well as rotation of the electron beam around the butt using a deflection system. The paper gives the schematic of welding in common vacuum and modes ensuring formation of fillet weld without reducing the pass section of an up to 40 mm diameter tube, including the case when the tubes extend above the tubesheet level.

Keywords: *EBW, electron beam, heat exchanger, tube and tubesheet, welding schematic, single and double refraction, deflecting system, circular and local scan*

At present two fundamentally different technologies of EBW of tubes to tubesheet have become accepted in industry. The difference between them consists in space-time orientation of the electron beam relative to tubesheet plane [1, 2]. In case of single refraction of the electron beam and its rotation around the butt joint by the deflection system relative to a stationary item (Figure 1, *a*) there is a dependence between penetration depth h_{pen}, distance from beam focusing plane to item f_b, tube diameter D_p, and refracted beam deviation in the weld root from tube-to-tubesheet butt Δk:

$$\Delta k = \frac{D_p}{2f_b} h_{pen}.$$

It is seen from this dependence that deviation of refracted electron beam in the weld root from tube-to-tubesheet butt increases with the increase of values

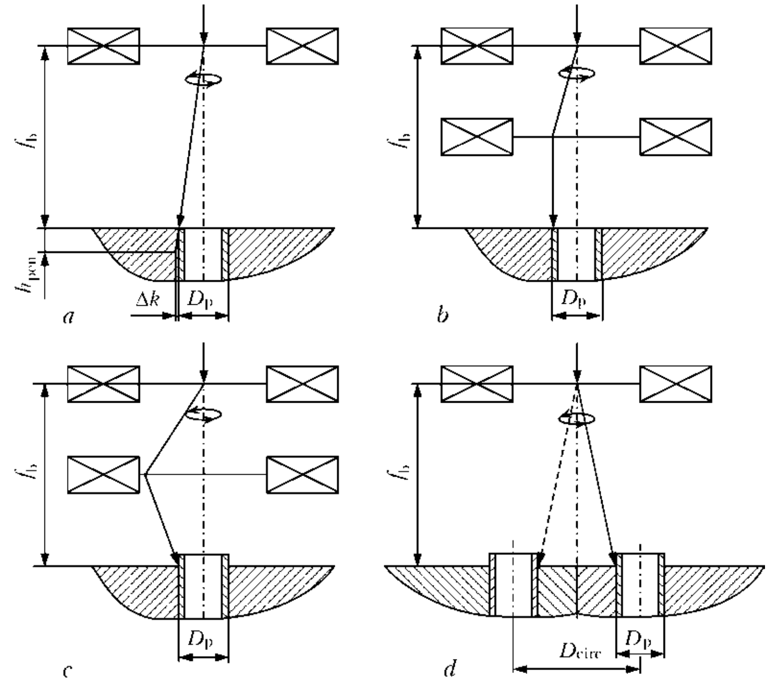

Figure 1. Schematic of EBW of tubes to tubesheets: *a* — single refraction of electron beam and its rotation around the butt; *b* — double refraction of electron beam and its rotation around the butt normal to tubesheet surface; *c* — double refraction of electron beam and its rotation around the butt for tubes extending above tubesheet surface; *d* — electron beam rotation with single refraction and its simultaneous displacement along coordinates *x* and *y* along diameter of circumference D_{circ} of shifted tube

D_p and h_{pen} and decreases with increase of f_b. Having selected focal distance f_b = 150 mm and penetration depth h_{pen} = 3.5 mm, we will have the data on the change of weld root deviation from the butt: at D_p = = 8 mm $\Delta k \approx 0.09$ mm, at D_p = 16 mm $\Delta k \approx 0.18$ mm, at D_p = 24 mm $\Delta k \approx 0.28$ mm.

In EBW of tubes with wall thickness δ = 1.0–1.5 mm to tubesheets by the schematic with single refraction of the electron beam (see Figure 1, *a*) in order to ensure $h_{pen}/\delta \geq 2$ ratio, it is necessary to reduce the diameter of beam circular scan d_c by $2\Delta k$ using deflection system, so as to align the weld root with the tube-to-tubesheet butt. This technological measure can lead to flowing of circumferential weld metal inside the tube and reduction of its pass section that is inadmissible in operation of heat exchangers. We believe it is possible to prevent metal flowing inside the tube by application of precision electron beam guns with accelerating voltage U_{acc} = 60 kV and pulsed welding mode [3], as well as limiting tube diameter by $D_p \leq 8$ mm. It should be noted that the precision of electron beam alignment with the circumferential tube–tubesheet butt was not more than 0.05 mm at single refraction and rotation using electromagnetic deflection system.

In EBW of tubes to tubesheets with double refraction of the electron beam and its rotation by the deflection system normal to tubesheet surface (Figure 1, *b*) we believe it is possible to eliminate Δk and prevent flowing of circumferential weld metal inside a tube of diameter D_p > 8 mm. The advantage of this technique is protection of anode–cathode accelerating gap of the electron beam gun from breakdowns during welding.

Schematic of EBW of tubes to tubesheets with double refraction of the electron beam and its rotation relative to a stationary product using a deflection system, shown in Figure 1, *c*, allows welding tubes extending above the tubesheet surface. After second refraction the electron beam is guided to the butt of tube and tubesheet at an angle to tubesheet surface, but already with shifting towards it.

Bead deposition on monolithic samples and welding of circumferential tube-to-tubesheet butt joints on PT-7M and PT-3V titanium alloys respectively, were performed in the laboratory unit with electron beam gun ELA-60/15 and Rogowski spherical optics [4], application of which allowed an essential improvement of beam current influence on electron beam focal point position. Two pairs of aligned deflection coils, located coaxially one above the other at 100 mm distance, were used as deflection system. At 63 mm inner diameter of the hole in the coils total height of deflection system was equal to 170 mm (Figure 2).

Control of electron beam focusing on the surface of flat samples and tubesheet at double refraction was checked visually by the brightness of circular scan pattern of diameter d_c = 8 mm with electron beam current I_b = 10 mA on a massive copper plate, located below the tubesheet surface at 2/3 of penetration depth h_{pen}. Such a technique allowed ensuring ratio $h_{pen}/\delta = 4$ without rolls of circumferential weld metal inside the tube on joints of PT-3V alloy tube with wall thickness δ = 1.5 mm to PT-7M alloy tubesheet.

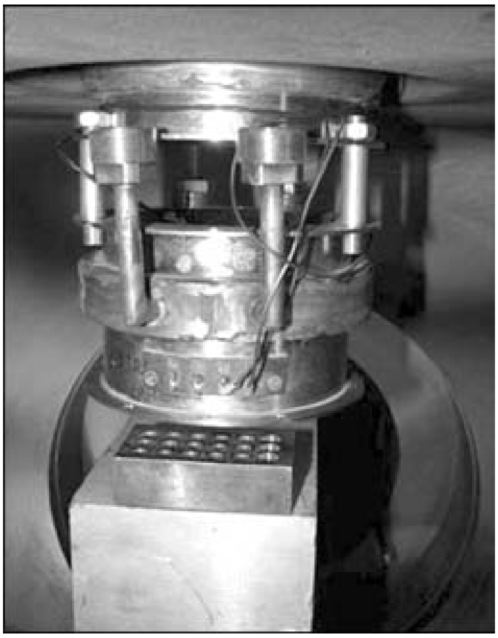

Figure 2. Appearance of deflection system with double refraction of the electron beam mounted on electron beam gun ELA-60/15

To study electron beam heat input and weld face bead width on tube-to-tubesheet welded joints a series of bead-on-plate welds were made by the electron beam with double refraction on monolithic samples from PT-3V titanium alloy at welding speed v_w = = 5–25 mm/s. Penetration depth was kept constant on the level of h_{pen} = 7.5 mm by changing beam current. As shown in Figure 3, heat input q/v_w and weld face bead width B_1 decrease abruptly with increase of welding speed, and starting from v_w = 15 mm/s they are practically stabilized. Minimum weld width reaches B_1 = 1.85 mm. Thus, in further investigations selection of the speed of welding of tube-to-tubesheet joints is performed from the condition $v_w \geq 15$ mm/s. It should be noted that the precision of the electron beam alignment with circumferential butt at double refraction and rotation using two electromagnetic deflection systems was not lower than at single refraction, and was equal to not more than 0.05 mm.

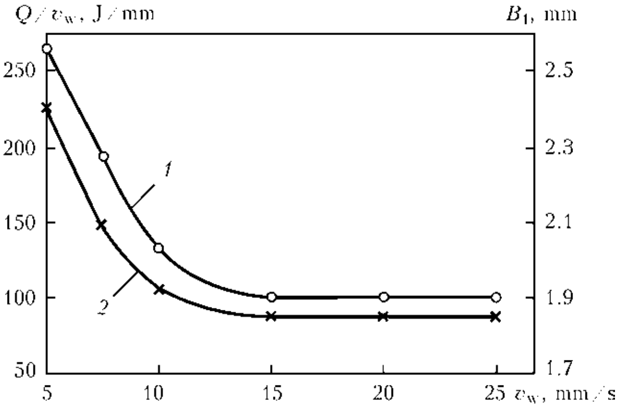

Figure 3. Dependence of heat input q/v_w of electron beam (*1*) and weld face bead width B_1 (*2*) on welding speed v_w in the following welding mode: h_{pen} = 7.5 mm, U_{acc} = 60 kV, I_f = 560 mA, d_c = = 10 mm and f_b = 200 mm

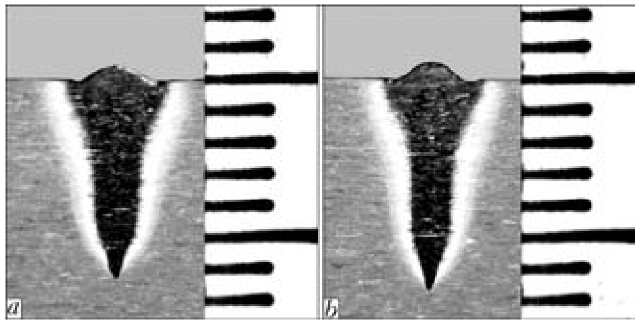

Figure 4. Transverse sections (×7) of beads on titanium alloy PT-3V made by EBW by the electron beam without refraction (d_c = 0 mm) (*a*) and with double refraction (d_c = 40 mm) (*b*) in the following mode: U_{acc} = 60 kV, I_b = 25 mA, v_w = 15 mm/s and f_b = 200 mm

With the schematic of welding with double refraction of the electron beam (see Figure 1, *b*), when after the deflection system the beam is directed normal to tubesheet surface (parallel transfer), the influence of beam double refraction on penetration geometry, and mainly — on penetration depth h_{pen} and weld face bead width B_1 should be studied. To solve this task, a series of bead-on-plate welds were made on a monolithic sample from titanium alloy PT-3V at diameter d_c = 20–40 mm of the electron beam circular scan in tubesheet plane. On transverse sections of the bead (Figure 4) it is seen that geometry of welds (h_{pen}, B_1) made without refraction of electron beam (d_c = 0) and with double refraction (d_c = 40) is practically the same. It leads to the conclusion that the schematic of EBW with double refraction of the electron beam can be recommended for industrial application in welding tubes to tubesheets at up to 40 mm tube diameter inclusive.

In EBW with single and double refraction of the electron beam tube-to-tubesheet welded joints with minimum (about 5 %) fluctuations of penetration depth along the weld length can be made by introducing a circular local scan with the speed not higher than that of welding [5]. Transverse dimensions of weld root part are determined, mainly, by diameter of circular local scan of the electron beam d_{loc}. It should be noted that this technique allows lowering the requirements to the accuracy of alignment of electron beam circular scan, d_c, with the circumferential butt to ±0.15 mm. The series of bead-on-plate welds made on a monolithic sample from titanium alloy PT-3V at variation of diameter of electron beam local scan in the range d_{loc} = 0–1.25 mm with local rotation frequency f_{loc} = 1000 Hz, allowed establishing the change of weld geometrical parameters (h_{pen}, B_1, B_{mid}) and possibility of selection of local scan diameter d_{loc} by width B_1 of weld face bead and width of weld middle part on half the penetration depth B_{mid}. As is shown in Figure 5, at local scan diameter d_{loc} = 0.5 mm welds can be produced with face bead width B_1 = = 2 mm and ratio $h_{pen}/\delta > 3$ at tube wall thickness δ = 1.5 mm. Flowing of circumferential weld metal inside the tube is eliminated.

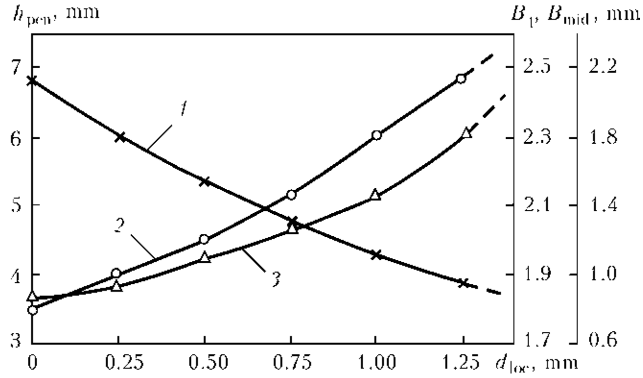

Figure 5. Dependence of penetration depth h_{pen} (*1*), weld face bead width B_1 (*2*) and weld middle part width on mid-depth of penetration B_{mid} (*3*) on diameter of electron beam local scan at U_{acc} = = 60 kV, I_b = 30 mA, v_w = 15 mm/s, I_f = 560 mA, f_b = 200 mm and d_c = 10 mm

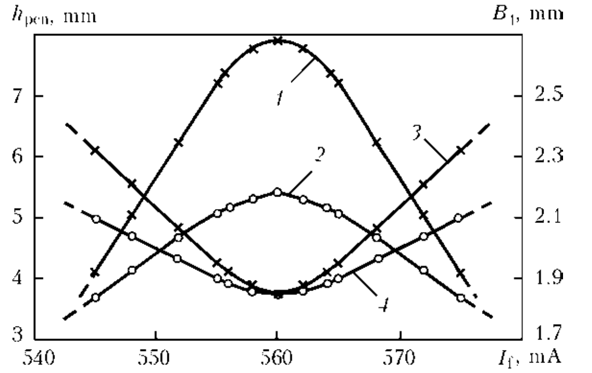

Figure 6. Dependence of penetration depth h_{pen} (*1*, *2*) and weld face bead width B_1 (*3*, *4*) at d_{loc} = 0 (*1*, *3*) and 0.5 mm (*2*, *4*) on focusing lens current I_f at U_{acc} = 60 kV, I_b = 30 mA, v_w = 15 mm/s, f_b = 200 mm and d_c = 10 mm

Influence of electron beam focal point position relative to the surface of tubesheet on penetration depth h_{pen} and width B_1 of weld face bead with double beam refraction was studied by producing a series of bead-on-plate welds on PT-3V titanium alloy at changing of focal lens current I_f from optimum value towards the smaller or greater values by approximately 3 %. Optimum I_f value provides maximum penetration depth h_{pen} and minimum width B_1 of weld face bead. As shown in Figure 6, maximum penetration depth h_{pen} = 7.8 mm corresponds to focusing current I_f = 560 mA and position of electron beam focal point below sample surface on 2/3 of penetration depth. Introduction of circular local scan d_{loc} = 0.5 mm reduces penetration depth by 1.47 times at preservation of face bead width B_1. Change of focusing lens current from optimum value by 0.9 % (ΔI_f = 5 mA) reduces the penetration depth by 0.6 (d_{loc} = 0) and by 0.2 mm (d_{loc} = 0.5 mm). Thus, introduction of a circular local scan of the electron beam allows an essential reduction of the dependence of penetration depth on focusing lens current. In addition, as is seen on transverse sections of the bead-on-plate weld (Figure 7) in EBW of tube-to-tubesheet joints with double refraction of the electron beam and circular local scan an increase of transverse dimensions of the weld middle and root part approximately by value d_{loc} = 0.5 mm is found.

EBW of tube-to-tubesheet joints of heat exchangers can be performed in the case, if a tube of diameter

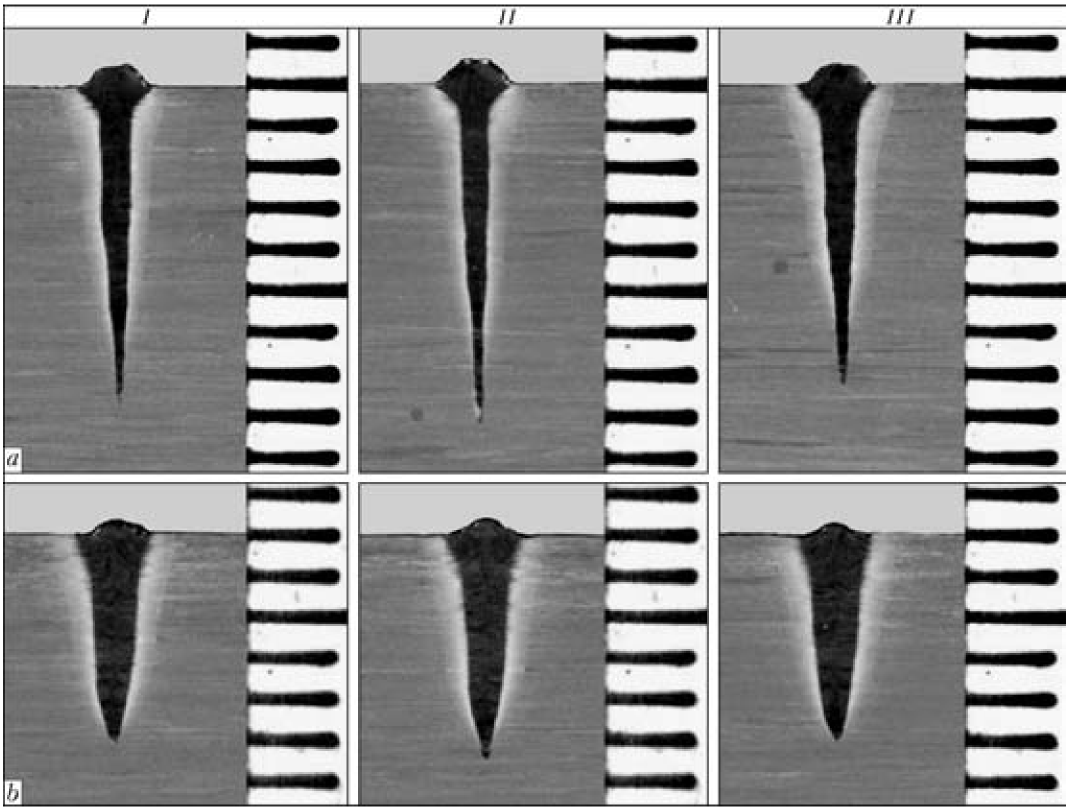

Figure 7. Transverse sections (×5) of bead-on-plate welds on titanium alloy PT-3V made by EBW with double refraction of the electron beam without local scan (d_{loc} = 0) (*a*) and with circular local scan (d_{loc} = 0.5 mm) (*b*) at I_f = 558 (*I*), 560 (*II*) and 562 (*III*) mA in the following mode: U_{acc} = 60 kV, I_b = 30 mA, v_w = 15 mm/s, d_c = 10 mm and f_b = 200 mm

Figure 8. Appearance of specialized system UL-178M for EBW of tubes to tubesheets

$D_p \geq 40$ mm protrudes above the tubesheet surface. To perform this operation the electron beam after the first refraction has to be deflected in such a way that in the refraction plane it would be deployed into a circle of diameter $d_c > D_p$. After second refraction the deflection system directs the beam at an angle to tube axis (see Figure 1, *c*). Weld root alignment with the tube–tubesheet butt is ensured by shifting of the electron beam towards the tubesheet.

In the case, when the tube extends above the tubesheet surface, a welding schematic can be used, at which a tube shifted relative to gun axis for distance $(D_p/2 + \Delta k)$ moves along coordinates x and y by diameter of circumference D_{circ} with simultaneous rotation of the electron beam with single refraction for alignment with the tube–tubesheet butt (see Figure 1, *d*). Such a welding schematic is implemented in specialized system UL-178M (Figure 8) developed at PWI. Two-level multiprocessor automated CNC + + PLC control system allows moving the heat exchanger unit by a certain program inside the chamber along coordinates x and y and controlling the power, focusing and deflection of the electron beam. As shown in Figure 9, in EBW of a tube of diameter $D_p = 27$ mm with 3 mm wall thickness from PT-7M alloy to tubesheet from PT-3V alloy the angle of electron beam deflection from the vertical axis was equal to 4°30′, and its displacement towards the tubesheet was $\Delta k =$ = 0.3 mm for alignment of the weld root with the butt of tube and tubesheet.

Figure 9. Macrosection (×3) of welded joint of protruding tube ($D_p = 27$ mm with wall thickness $\delta = 3$ mm) with tubesheet produced by electron beam with single refraction and displacement of the tube along coordinates x and y by the diameter of its circumference in the following mode: $U_{acc} = 60$ kV, $I_b = 30$ mA, $v_w = 15$ mm/s and $f_b = 200$ mm

CONCLUSIONS

1. EBW of joints of tube to tubesheet from titanium alloys with double refraction of the electron beam and with rotation around the butt using the deflection system with the stationary workpiece provides formation of the weld without change of penetration geometry up to tube diameter $D_p = 40$ mm inclusive.

2. Minimum values of electron beam heat input and weld face bead width are provided at welding speed $v_w \geq 15$ mm/s.

3. Application of circular local scan of the electron beam at double refraction allows reducing the variation of penetration depth along the weld length, increasing transverse dimensions of its middle and root part and decreasing the dependence of penetration depth on focusing lens current.

4. Double refraction of the electron beam and its rotation around the butt of tube–tubesheet using the deflection system at stationary position of the item allows performing EBW in the case, if the tube protrudes above the tubesheet surface.

5. At such a position of the tube, EBW can be performed by programmed displacement of the tube along coordinates x and y around the circumference with simultaneous rotation of the deflected electron beam around the butt.

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DEFORMATIONS OF WELDED JOINTS IN MULTILAYER ELECTROSLAG WELDING

S.M. KOZULIN and **I.I. LYCHKO**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The results of experimental determination of significance and character of development of deformations in multilayer electroslag welding are given. It was established that the general nature of final distribution of movements of edges being welded is similar to one-pass electroslag welding.

Keywords: *multilayer electroslag welding, transverse deformations, onward movement, shrinkage of weld, angular rotation of edges*

Assurance of accuracy of geometric sizes of products in manufacture or restoration of massive structures applying electroslag welding (ESW) is the important task of increasing the efficiency of welding production.

The method of proportioned counteraction [1], successfully applied in the production, provides accuracy of geometric sizes of large welded products which is approximated to that of mechanical treatment.

However, during repair of large parts of machines using multilayer ESW (MESW) it is practically impossible to apply the mentioned method, as far as specified conditions of fastening edges being welded due to presence of forming metallic crosspieces hindering free shrinkage of crystallizing weld metal and also due to not simultaneous rewelding of the whole thickness of a product cannot be reproduced [2].

As there is no methods of calculation, the expected deformations in MESW were studied experimentally. In conventional ESW the transverse deformations are of the greatest importance [3, 4], leading to the decrease of a gap between parts being joined, transverse shrinkage and angular deformations in the plane of a butt being welded. The onward movement of parts being joined occurs most intensively at the initial period of welding. For example, during the first 40–60 min the primary shrinkage is observed, which is 60–70 % of the whole onward movement of edges. With increase of thickness of metal being welded the onward movement increases [1].

Angular deformations (rotation in the plane of edges being welded) result in closing a gap between edges. These deformations as well as onward movements are most intensive at the initial period of welding. Then, with increase in resistance of a crystallized part of a weld, the rotation is decreased and in some cases can be completed even before completion of welding [5]. The angular rotation depends to a great degree on the conditions of fastening edges, and also welding conditions and can reach 0.02–0.03 rad (1–2°) and lead to dangerous probability of short-circuiting of nozzles to the product. In welding of finally treated large-size billets the unaccounted residual angular deformations can cause considerable deviations of geometric sizes of a product from its drawing sizes.

While performing MESW the same types of deformations are formed as in one-pass ESW welding. However such factors are added to the typical conditions of formation of deformations as non-simultaneous rewelding of all thickness of a butt (constant increase of resistance to shrinkage of crystallizing metal in making each layer), succession (sequence) of layout of layers and possibility of rotation of edges in the plane perpendicular to a multilayer weld (Figure 1).

During experimental investigation of temporary and residual deformations such types of deformations as buckling of an edge and deformations caused by structural transformations were considered to be accounted in the main types of transverse deformation. In the present work the longitudinal deformation (shortening along the length of a weld) was not considered as far as it shows a great influence on accuracy of manufacture of welded structure in ESW of closed contours (for instance circumferential welds), however in ESW of rectilinear butts it is negligible [3].

Welding of full-scale specimens simulating a large defect (through crack) was performed by a consumable nozzle using machines A-645M and A1304 and power source TShS 3000/3. Specimens of steels 35L and

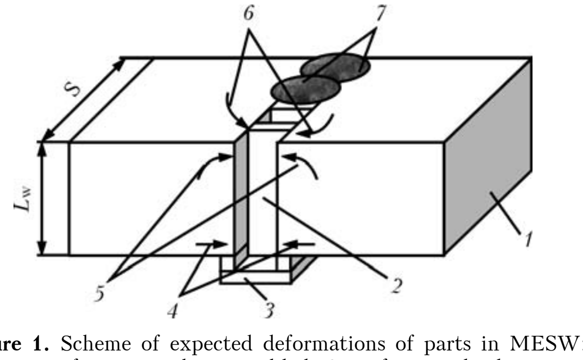

Figure 1. Scheme of expected deformations of parts in MESW: *1* — part of specimen being welded; *2* — forming bridge piece; *3* — input technological pocket; *4* — transverse shrinkage Δb; *5* — rotation of parts being welded in the plane β of a butt; *6* — rotation of parts being welded γ in the plane perpendicular to welded multilayer weld; *7* — made layers of a weld; S, L_w — thickness and length of welded butt

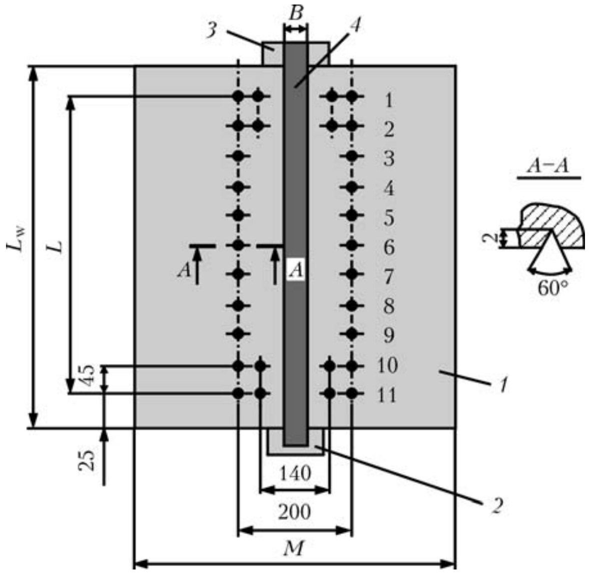

Figure 2. Scheme of reference marks arrangement (1–11) for measurement of onward movements of edges being welded: *1* — parts being welded; *2* — input pocket; *3* — run-out tab; *4* — forming bridge piece; L_w = 500–650 mm; M = 1200–1400 mm, L = 450–600 mm; B — welded gap

34L-ESh were of the following sizes, mm: thickness — 300 and 600, height of a butt — 500–650, width — 1200–1400. Depending on the thickness the butts were rewelded , respectively, for four and seven passes with a different sequence of layout of layers at specific heat input of MESW E_w = 110–170 kJ/cm^2. Welding condition parameters were controlled using an information-measuring system SU-150 [6].

The movement of edges was measured on the reference marks (indentations) using a caliper having an accuracy of 0.01 mm. Reference marks were made on both sides of edges being welded on the base of 140 and 200 mm (Figure 2). The measurements were performed every 20 min in the process of making a layer (weld) and also before beginning of making each next

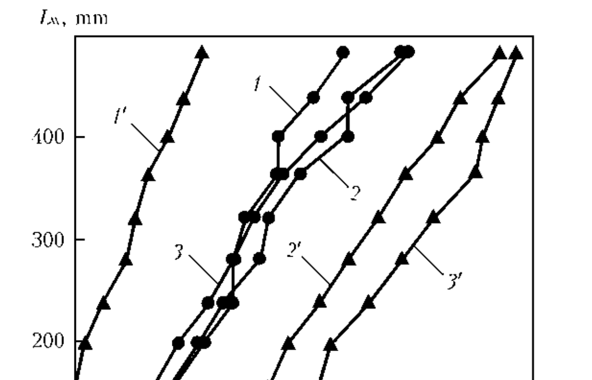

Figure 3. Distribution of movements of edges being welded Δ in performing MESW with layout of layers from one edge of a butt to another one: *1–3* — movement of edges on the side I after making the first, second and fourth layers; *1′–3′* — the same on the side II

layer. The actual onward movement (transverse shrinkage of a weld) Δ*b* was defined as difference in measurements of distances between reference points of the lower parts of edges on both sides of a butt. The actual rotation angle β of parts being welded was determined after layout of each layer according to the known expression of the work [7]:

$$\beta = \frac{\Delta b_{\rm a.t} - \Delta b_{\rm a.b}}{L}\ [\text{rad}], \qquad (1)$$

where $\Delta b_{\rm a.t}$, $\Delta b_{\rm a.b}$ is the actual value of onward movement of edges, respectively, at the top and bottom of the butt, mm; L is the distance between points of measurements, mm.

It was established that the onward movement and rotation of parts in ESW are not related. Therefore, onward movements and rotation angles of parts in MESW performance were measured on the same specimens according to the methods given in the work [7].

General character of deformations of edges being welded is similar to one-pass ESW [5]. However, the presence of forming metallic bridge pieces in a gap, hindering the free shrinkage of a weld, and also method of filling a groove by filler metal cause the definite changes in the character of deformation of products.

Figure 3 shows results of movements of reference points depending on their coordinates at the edge and coordinates of a length of produced layers in layout of the latter from one edge of a butt to another one. The vertical axis is a starting position of an edge before making the first layer. The movement of one edge is plotted along the horizontal axis, e.g. a half of a measured value. In contrast to one-pass ESW [5] the noticeable opening of lower edges (see Figure 3, curve *1′*) is observed in the mentioned case after making the first layer. It can be explained by the following reasons. As far as the thickness of a layer being produced is much smaller (by 4–15 times) than the thickness of the whole butt, the forces arising in shrinkage of metal of the first layer of a weld in the upper part of a butt overcome the resistance of initial area of a layer and bring apart the lower edges. In layout of next layers the resistance grows and lower edges are first returned to initial position and then continued to bring together. Besides, the bends of a moving curve in MESW are practically absent at the beginning and end of a weld (see Figure 3), characteristic of the conventional ESW [4, 5], e.g. the uniform (linear) increase of angular deformation takes place along the length of a butt in layout of each next layer.

It is seen from Figure 4 that the final movement of edges (after rewelding of the whole butt) on the opposite sides of a butt is different.

For a possibility of accounting for the expected shrinkage and rotation of edges the onward movement of lower parts (reference marks 11, Figure 2) of edges being joined Δ*b* and their rotation β depending on sequence of making layers and their quantity were studied.

In successive layout of layers from one edge of a butt to another one the onward movement of edges (transverse shrinkage) of the opposite edges of a butt occurs not in the same way (Figure 5, *a*). The shrinkage of edges, located on the side where the first layer was made, is almost completely finished after layout of this layer and in layout of next layers it does not change its value (Figure 5, *a*, curve *1*). In this connection the final shrinkage of mentioned edges is not large and does not exceed 1.5 mm. The onward movement of edges, located on the side of the last laid layer of the multilayer weld, is increased gradually with increase of a number of layers (Figure 5, *a*, curve *2*). It is necessary to note that after making the first layer some opening of edges is observed caused by their rotation as a result of shrinkage relative to a longitudinal axis passed through the center of the first layer. After layout of the third layer the further increase in onward movement does not occur that is due to the increased resistance to shrinkage of metal of formerly laid layers. The onward movement of mentioned edges in layout of the next layers does not exceed 2.4–2.5 mm.

In MESW with layout of layers from the center of a butt to its edges the movement of edges, located on the opposite edges of a butt, has the more complex character. After welding of a central hole the shrinkage is negligible and sufficiently uniform on the both sides of a butt, however after making the second (adjacent) layer the edges being welded, on the side of which this layer was laid, are brought together, while the opposite ones are brought apart (Figure 5, *b*). After layout of the third layer (on the opposite side from the central one) the contrary situation is observed. However, the edges, located on side I (Figure 5, *b*, curve *1*) are brought apart to a less degree than the opposite ones after layout of the second layer. The absolute value of the onward movement of mentioned edges after layout of the third layer is several times lower here than that of the movement of the opposite edges. It is connected with non-simultaneous making of the second and third layers. After layout of the fifth and next layers the edges, on the side of which the second layer was laid, are returned to the initial position and remained in that way until completion of rewelding of the whole butt (Figure 5, *b*, curve *1*). The onward movement of edges, opposite to those mentioned above, remains almost unchanged after layout of the fifth layer until completion of rewelding of the whole butt is finished (Figure 5, *b*, curve *2*). After complete cooling of welded specimen the shrinkage of edges, on the side of which the second layer was made, was 0.5 mm, and the shrinkage of the opposite ones was 1.15 mm. After high tempering and complete cooling of the specimen the shrinkage of edges on the side of the second layer was 1 mm, and that on the other side was

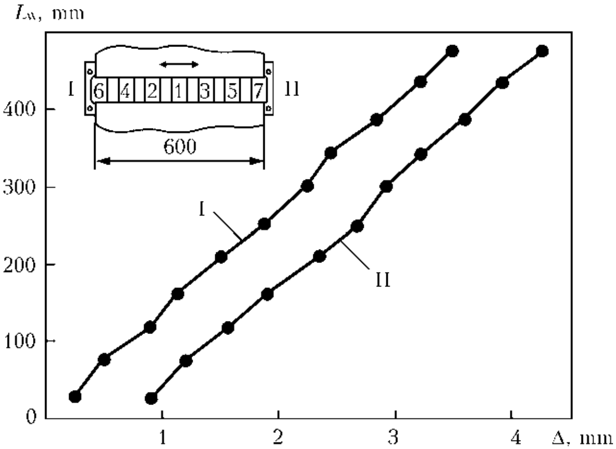

Figure 4. Final distribution of movements of edges being welded in MESW with layout of layers from the center of a butt to the edges: I, II — numbers of sides of a butt being welded

2.5 mm. It is possible to remove difference in shrinkage of the opposite sides of the welded joint and to reduce its absolute value by making simultaneous layout of each pair of layers on the opposite sides of the first layer, e.g. symmetrically to vertical axis passed through the center of a butt.

The experimental investigation of dependence of the angular rotation of edges β (see Figure 1) on the time of welding and quantity of made layers of a multilayer weld showed that during layout of layers from the one edge of a butt to another one the rotation of edges is more intensive in making the first two layers (Figure 6). During layout of further layers the rotation of edges is practically interrupted and remains unchanged up to the completion of the whole welding cycle which is due to the increased resistance of metal

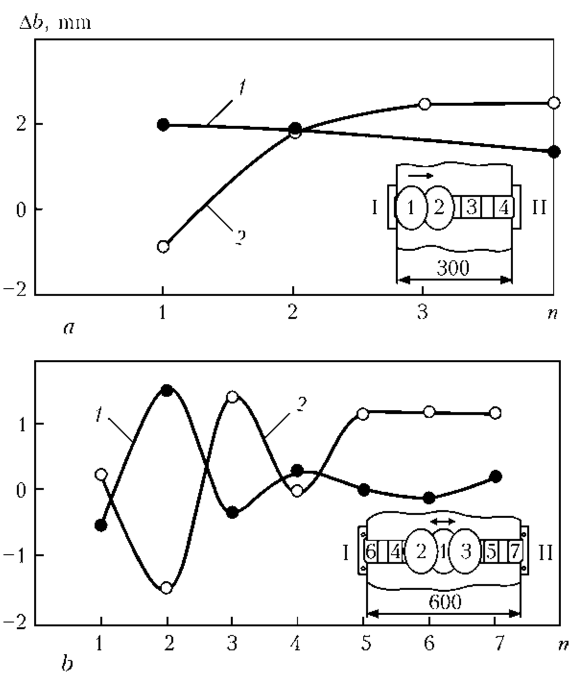

Figure 5. Dependence of transverse shrinkage Δ*b* of edges being welded on the number *n* of produced layers of MESW: *a* — layout of layers from one edge of a butt to another one; *b* — layout of layers from the center of a butt to the edges (at random); *1* — movement of lower parts of edges on the side I; *2* — the same on the side II

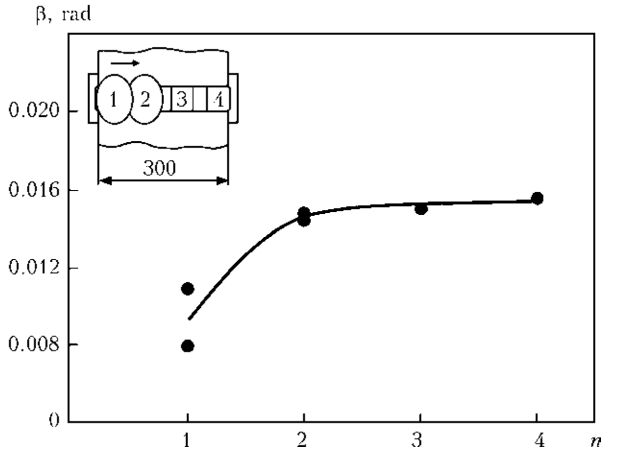

Figure 6. Dependence of rotation angle β of edges being welded on the number n of laid layers of a multilayer electroslag weld performed by layout of layers successively from one edge of a butt to another one

of made layers. Thus, after rewelding of the whole butt the total angular rotation of edges at thickness of billets of 300 mm and more is 0.0156 rad that is in compliance with the angular rotation of edges in one-pass ESW at the value of a specific counteraction moment of 40 kg/cm [1]. It was established that during MESW performance from the center of a butt to its edges the intensive angular rotation of edges occurs in making the first four layers (Figure 7). In that period the increase of rotation angle of edges β is almost in a linear dependence on the number of laid layers (thickness of rewelded part of a butt). The layout of next layers does not almost change the rotation angle attained at the moment of completion of the fourth layer (see Figure 7). Only after the last (external) layers the negligible increase in β is observed. However, considering the fact that before the moment of completion of the last layers 80 % of the whole section has been already rewelded (e.g. 480 mm of butt thickness) it should be noted that the mentioned-above β increase can hardly characterize the actual value of mutual rotation of billets being welded after layout of the external layers. Most probably, the local bending of external areas of edges is observed in this case as a result of a lower rigidity of fastening

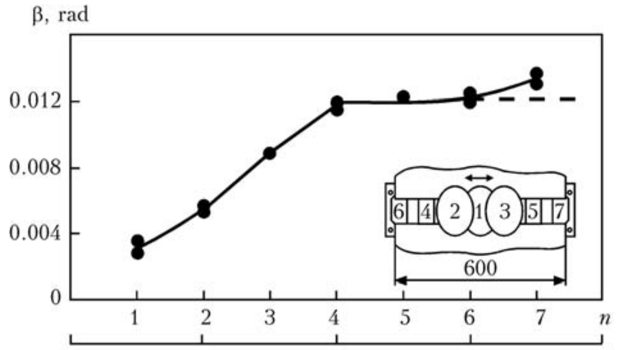

Figure 7. Dependence of rotation angle β of edges being welded on the time of welding t and number n of layers of multilayer weld in MESW with a random layout of layers from the center of a butt to its edges

of the external surfaces of edges. Besides, it is necessary to consider that during measurements of the onward movements of edges during making the external layers an error in measurements can appear as a result of influence of edges heating in the region of location of reference points.

Thus, the total angular rotation of billets after MESW performed in the direction from the middle of a butt to edges for the parts of thickness of 400 mm and more will amount to about 0.0134–0.0137 rad that is in compliance with the angular rotation in one-pass ESW at the value of counteraction moment, equal to 70–87 kg/cm [7].

The investigation of dependence of rotation angle of edges β on the length of welded area of a layer and time of welding showed that in making the first layer the intensive mutual rotation of billets takes place causing edges bringing together at the top of a butt (Figure 8). In the period of a slag pool passing through the middle of the butt length (groove depth) the reverse process is observed (bringing apart of edges). After the slag pool passing from the middle of groove depth, the change in sign of rotation takes place again and by the moment of completion of the first layer the edges of parts being welded are returned to the initial position (see Figure 8, curves *1* and *2*). With fulfillment of next layers the sufficiently uniform increase in β takes place achieving 0.013 rad by the moment of layout of the fifth layer. In making the fifth layer the rotation angle of edges is firstly a bit increased, then after rewelding of half of height of a butt β begins to decrease and it is stabilized by the end of welding (Figure 8, curves *3* and *4*). In making

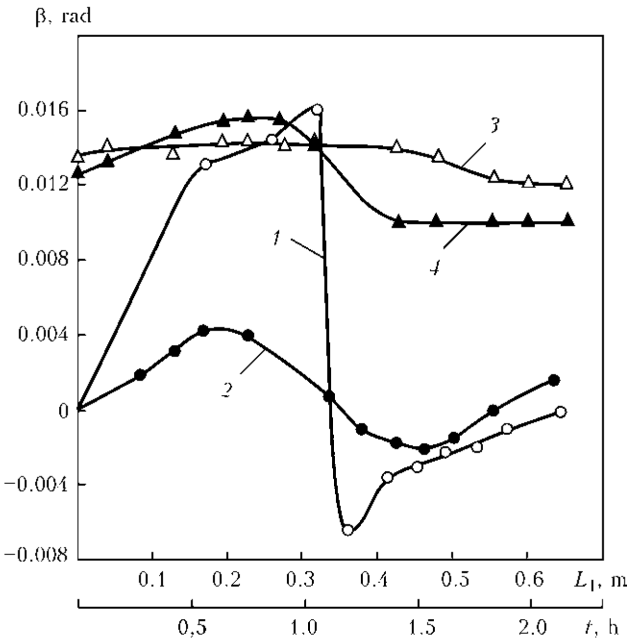

Figure 8. Dependence of rotation angle β of edges being welded on the length of a layer L_l and time of layout t of the latter in MESW with a random layout of layers from the center of a butt to its edges: *1*, *2* — rotation angle of the opposite edges in making the first layer; *3*, *4* — the same in making the fifth layer

the last layers the rotation angle of edges does not almost change the achieved value.

As was stated earlier, in MESW the appearance of angular rotation of edges γ in the plane perpendicular to welded multilayer joint is possible (see Figure 1), which is due to a non-simultaneous filling of a butt with filler metal across the thickness. The appearance of this kind of deformation can inadmissibly change geometric sizes of large-sized product, cause, for example, the increased fracture of a band and obliquity along the generatrix which will increase later the wear of rolling surface and decrease its service reliability. Therefore, it is necessary to know the level of residual angular deformation to determine the optimal shape of edge groove for MESW.

The actual angular rotation γ of billets being welded in the plane, perpendicular to welded multilayer joint, was determined after completing each layer according to the formula

$$\gamma = \frac{\Delta b_1 - \Delta b_2}{S} \text{ [rad]}, \quad (2)$$

where Δb_1, Δb_2 are the actual onward movements of upper parts of edges on the opposite sides of a butt, mm (see reference marks 1 in Figure 2); S is the thickness of a product being welded, mm.

The results of carried out measurements showed that at successive layout of welds from one edge of a butt to another one the angular rotation of edges takes place with change of the rotation direction (Figure 9). After making the first layer the opening of a gap occurred (rotation of billets being welded relative to longitudinal axis of the first layer) and edges bringing together occurred after layout of the second and next layers. The total value of angular rotation after MESW of the specimen of 300 mm thickness was 0.008 rad (Figure 9, curve *1*). To compensate the considered type of deformation it is necessary to account for the expected difference of shrinkage in the process of assembly of billets for welding, having formed, for example, a wedge-shaped gap between edges being welded in a horizontal plane or to perform preheating of that side of a butt where the last layer will be performed. The results of measurements of rotation angle γ of edges in layout of layers into the groove from the center of a butt to its edges (at random) showed that while making the first four layers the change of direction of rotation of billets was observed twice (Figure 9, curve *2*). After making the fifth layer the rotation angle γ reached its limiting value and did not increase later. This was due to the increased resistance of rotation of a metal of formerly laid layers, and also due to the selected most favorable sequence of layers layout (at random from the center of a butt).

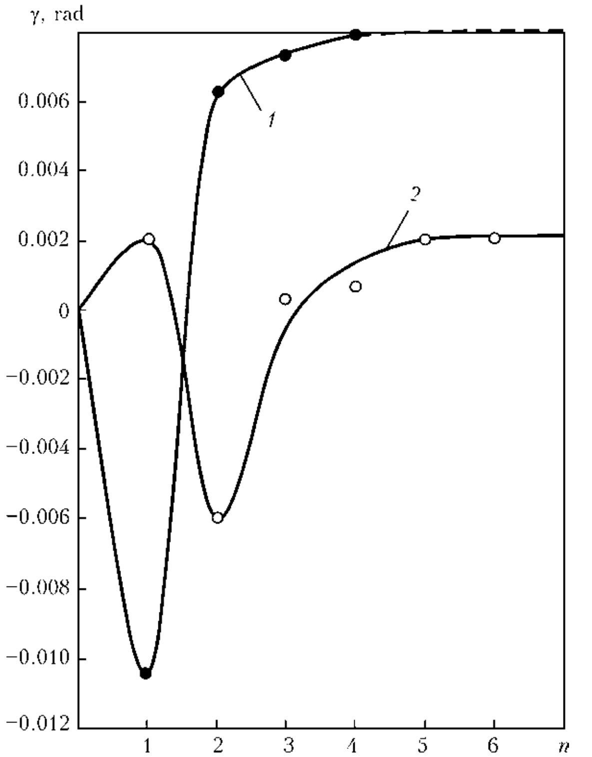

Figure 9. Dependence of rotation angle γ of edges being welded in the plane perpendicular to welded multilayer weld on sequence of layout of layers of a multilayer electroslag weld from one edge to another one (*1*) and from the center of a butt to its edges (at random) (*2*)

CONCLUSIONS

1. It was established that common character of final distribution of movements of edges being welded is similar to one-pass ESW. However, in MESW after making the first layer the noticeable bringing apart of the lower edges is observed and after layout of the second and next layers their bringing together is observed, which was gradually increased up to the completion of cycle of the whole specimen welding.

2. In MESW the bends of curve of final distribution of movements at the beginning and end of a weld, characteristic for conventional ESW, are almost absent, i.e. along the length of a butt in layout of each layer the uniform increase of angular deformation is occurred.

3. While performing multilayer ESW from the center of a butt to its edges the intensive angular rotation of edges β takes place during making the first four layers, and after layout of the fifth layer the β value is stabilized and does not change its value up to the completion of welding of the whole butt.

4. The lowest values of deformations (onward movement Δb, angular rotation of edges β and γ) can be obtained at simultaneous layout of pairs of layers of multilayer electroslag weld symmetrically from the center of a butt to its edges.

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DETACHABILITY OF SLAG CRUST IN ARC WELDING (Review) Part 1. Mechanism of Chemical Adhesion of Slag Crust to Weld Metal

S.I. MORAVETSKY
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The review is dedicated to analysis of existing notions about the mechanism of chemical adhesion of the slag crust to the weld metal in arc welding. An attempt has been made to detail this mechanism, allowing for the available data on the effect on it by phase composition of the slag crust. It is noted that elimination of chemical adhesion of the slag crust to the weld metal can be achieved by selecting the optimal combination of chemical composition of the slag and its oxidising potential.

Keywords: *automatic submerged-arc welding, multipass welding, narrow groove, alloyed steels, slag crust, detachability, chemical adhesion, phase composition, oxidising potential*

In development of welding technologies, welding consumables are chosen on the basis of a set of welding-operational properties, among which detachability of the slag crust is a key one.

Poor detachability of the slag crust decreases the productivity of welding operations and increases the probability of formation of exogenous non-metallic inclusions in the multipass weld metal. The character of detachability of the slag crust sometimes determines practicability of a welding technology and, in particular, the possibility of producing thick-walled narrow-groove butt welded joints. In this connection, investigations of the causes of poor detachability of the slag crust and search for the methods to improve this process have been the subject of fundamental research efforts conducted in the last sixty years.

This review is aimed at choosing the baseline approach to development of the flux for welding thick-walled narrow-groove butt joints on alloyed steels, the use of which could provide satisfactory detachability of the slag crust.

Some studies [1, 2] consider chemical bond of slag to the weld metal to be one of the causes of difficulties in removal of the slag crust from the surface of a welded joint. The mechanism of this phenomenon is described in study [1], which suggests that is it identical to the known mechanism of adhesion of oxide systems to metal, e.g. in enamelling of vessels or formation of burn-on on the surface of ingots cast into ceramic moulds. One of the characteristic peculiarities of the said mechanism is formation of a thin film of oxides of elements of the metal phase on the metal surface [1, 3–5]. Another process that is often considered to cause adhesion of the slag crust to the weld metal in welding is epitaxial crystallisation of slag phases on the oxide film as a substrate, these slag phases fitting the principle of structural, orientation and size correspondence (SOSC) to the oxide film [1, 6, 7]. SOSC of crystalline materials is ensured by the same type of their crystalline lattice, providing that the unit cell sizes differ but insignificantly. Therefore, according to [1, 6, 7], chemical bond of the slag crust to the weld metal in welding of steels can be eliminated by using a slag having the minimal oxidising ability and containing no compounds that fit the SOSC principle with respect to oxides on the surface of the weld metal made on steel (e.g. spinels).

Numerous investigations were carried out to determine the presence of correlation between phase (chemical) composition of the slag crust and character of its detachability [8–12]. It follows from the above studies that in the cases of unsatisfactory detachability of the slag crust its phase components do not fit the SOSC principle with respect to the most typical oxides forming on the surface of the weld metal. And vice versa, if detachability is good, it is almost always possible to determine which phases in the slag crust fit the SOSC principle. The data of study [13] on the effect of the rutile content of slag of the $CaO-CaF_2-SiO_2-TiO_2$ system on detachability of the slag crust contradict the obtained results [9]. Analysis of the results of studies [9–13] shows that it is by no means always possible to establish the clear relationship between phase composition of the slag crust and its detachability from the weld metal.

One of the conditions for epitaxial growth of oxides on the surface of the weld metal is a very low rate of reaction [14], as well as peculiarities of the diffusion and relaxation processes occurring in subsurface contact layers of the metal and slag [15]. The epitaxial growth of oxides is caused by chemical transformation taking place on the surface of the weld metal at insignificant changes in configuration of ions in a new (oxide) phase, compared to the initial (metal) phase [14]. Some mismatch of sizes of their lattices is compensated for by elastic alignment of the spliced crystal faces, or by formation of misfit dislocations within the contact zone [15], which, as a rule, is a cause of adhesion of thin oxide films to metals. However, it can be assumed that it is the diversity of the oxidation conditions in welding [8] and welding parameters [1] that leads to formation of higher oxides with different types of lattices in composition of the oxide film, as well as to a substantial change in thickness of the oxide film. All of these factors promote cleavage of the film and improvement of detachability of the slag crust. Hence, the similarity of metal and conjugate oxides in the SOSC principle is not always a sufficient precondition for deterioration of detachability of the slag crust in welding.

The authors of study [16] consider formation of mostly coordination-covalent chemical bonds on the surface of contacting materials to be the necessary condition for joining metallic materials to oxide systems. In this case both basic and acid oxides can serve as reagents. The technology for joining metal to glass [17, 18] provides for formation of a film of basic oxides that are reactive with respect to the key component of glass, i.e. covar SiO_2, on the metal surface. Joining of glass to covar takes place at $T \cong 873$–1473 K, at which the glass grows soft. Basic oxides reacting with SiO_2 form iron from the covar components. As follows from study [17], a strong joint between the glass and covar is provided by the following chemical reactions:

$$\frac{2}{3}\,Fe_3O_4 + SiO_2 \rightleftarrows 2FeO{\cdot}SiO_2 + \frac{1}{3}\,O_2;$$

$$2FeO + SiO_2 \rightleftarrows 2FeO{\cdot}SiO_2.$$

Based on the similarity of physical-chemical conditions for formation of the high-quality glass-metal joints and conditions taking place on the surface of contact of the weld metal with the softened slag in arc welding, it can be assumed that chemical bond of the slag crust to the weld metal can cause, to a large degree, the reactions identical to the above ones. As a rule, fluxes contain, in addition to SiO_2, also other components that enter into reaction with Fe_2O_3 and FeO to form complex oxides of the type of $Al_2O_3{\cdot}FeO$, $MgO{\cdot}Fe_2O_3$, etc.

In case of poor detachability of the slag crust, the weld surface in contact with the slag was found to acquire a characteristic microrelief [10, 19]. Peaks are formed from grains of the weld metal, and valleys correspond to the grain boundaries. The grain-boundary regions of metal are rich in elements that are present in the form of oxides only in the flux. These are aluminium, calcium, magnesium and sodium. An increased content of reactive elements that transferred from the weld metal (titanium, chromium, niobium and vanadium) was also detected. When using slags that provide good detachability of the slag crust no

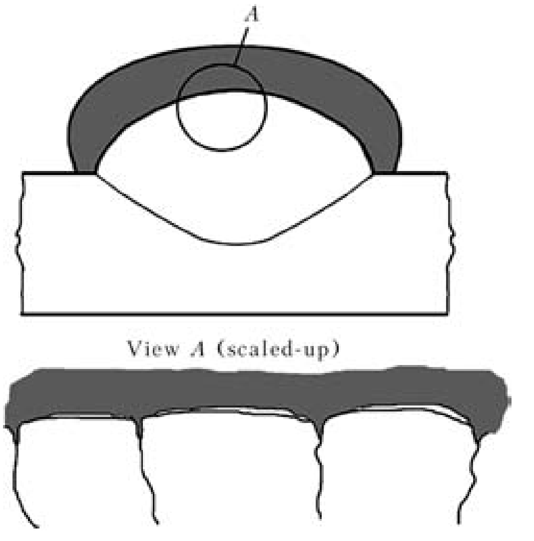

Figure 1. Schematic of adhesion of the slag crust to the weld metal caused by leading oxidation of the grain-boundary phase of metal with «rooting» of a non-metallic material into the grain boundaries

enrichment of grain boundaries with elements contained only in the slag, no segregation of alloying elements of the weld, and no presence of microrelief on the weld surface were observed. Based on these facts, the authors of study [19] assume that the slag crust chemically bonded to the metal surface is fixed locally: its main mass has the non-metallic material branches «rooted» at some depth into the boundaries of the sub-surface grains (Figure 1). In this case there is no adhesion between the slag and grain body (at a distance from the boundary).

Properties of the oxide film are determined by the ratio of a volume of oxide to a volume of metal consumed for formation of the oxide, V_o/V_m [3–5, 14]. V_o/V_m = 1.5–2.0 or more for many metals that can be components of steel [3]. Therefore, as the oxide film grows thicker, it may separate because of increase in shear stresses. Steels that undergo $\alpha \rightleftarrows \gamma$ transformations have substantially changing crystalline lattice parameters. For example, the value of parameter a of unalloyed γ-Fe at 900 °C is 0.3645 nm, whereas this parameter of α-Fe at room temperature is equal to 0.28606. It seems that these and other factors do not favour increase in physical bond of the oxide film to the weld metal.

It is a known fact that the grain boundaries are characterised by abnormally high diffusion permeability of materials. The ratio of diffusion coefficients at the grain boundary and in the bulk of grain, Δ'/Δ, amounts to $1{\cdot}10^3$–$1{\cdot}10^5$, and increases with a decrease in temperature. For α- and γ-Fe a substantial excess of Δ′ over Δ persists at a temperature of up to 1200 °C. Also, it is well-known that the thermal etching grooves form at the grain boundaries because of surface tension and diffusion [20, 21]. Considering the above facts and experimental results [11], the hypothesis of a local character of sticking of the slag crust to the weld metal [19] seems highly probable.

Examination of the slag–weld metal contact surface by the X-ray microanalysis and electron diffraction analysis methods showed that a thin (0.2 μm) intermediate oxide layer forming between the weld metal and slag crust at its poor detachability may consist of TiO, (Fe, Mn)O·Cr_2O_3, (Fe, Mn)O·V_2O_3, (Fe, Mn, Ni)]O·(Cr, Fe)$_2O_3$, etc. At good detachability of the slag crust the presence of the oxidised interlayer on the metal surface was not detected [7, 8].

Similar examinations performed by the secondary ion emission mass-spectrometry method in submerged arc welding with flux AN-348A of steel with a considerable content of vanadium revealed that the interlayer consisted of VO. A very high intensity of a flow of such ions as MnO^+, Mn^+, Fe^+ and FeO^+ is related to a defective structure of this interlayer and «lack of vanadium cations» [22]. The intensity of the flow of ions Si^+, FeO^+ and Mn^+ is 1.8, 3.7 and 9.7 times higher on the surface of the slag crust in contact with the weld metal than on its external surface, respectively. This suggests that the interlayer contains complex oxide compounds of the type of vanadates, manganates, silicates, spinels, etc.

If the weld is alloyed with elements having a higher affinity for oxygen (manganese, chromium, vanadium and titanium) than iron, the oxide film within the zone of contact of the softened slag with the solidified metal forms as a result of preferential oxidation of the most reactive of alloying elements with the slag, this being accompanied by formation of a relatively wide zone with a low content of this element near the surface of the weld metal [23]. In the weld on carbon steel, oxidation with slag causes appearance of the zones depleted in carbon, manganese and silicon [1].

Based on the above investigation results, the mechanism of formation of a strong joint between the slag and deposited metal seems to be as follows. The reaction of preferential oxidation of the most reactive alloying elements of an alloy takes place on the surface of contact of the softened slag with the solidified weld metal (region *ED* in Figure 2) due to the excessive

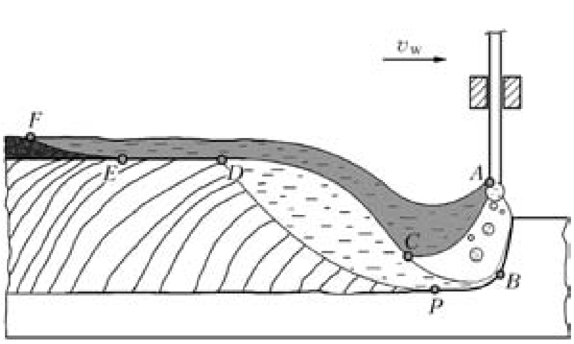

Figure 2. Schematic of the slag to weld metal interaction zones: *ABPC* — zone of high-temperature chemical reactions between slag and metal; *ABC* — zone of arcing and reactions between slag and metal at the stage of a droplet; *DPC* — zone of low-temperature reactions at the stage of the weld pool; *DP* — weld pool crystallisation front; *FE* — weld pool solidification front; *DC* — surface of contact between the molten slag and molten metal; *ED* — surface of contact between the molten slag and solidified metal

content of ions O^{2-}. The rate of diffusion flows of metal cations and oxygen ions at the grain boundaries is much higher than in the bulk of grain with a relatively perfect structure, this causing the leading oxidation of exactly the grain-boundary phase of metal to form the «roots» of a non-metallic material at some depth in the grain boundaries. The process of formation of oxides is accompanied by diffusion of the most reactive alloying elements from the central volumes to an interface of the weld metal with slag, as well as by formation of the zone with a decreased concentration of these elements in metal. The surface grains are characterised by the presence of diffusion flows from the bulk of grain to its boundary. And it is this fact that explains the final distribution of a reactive alloying element described in study [10].

Simultaneously with their formation, oxides interact with other excessive ions of the slag phase. The products of interaction are complex oxide compounds (e.g. MeO·Me_2O_3 and MeO·MeO_2). The fist constituent of such a complex belongs to the oxide film on the weld metal, and the second contains a component of the slag phase. In turn, the main mass of the slag crust strongly fixed to this component forms on the surface of the interlayer consisting of complex oxide compounds.

Of undoubted interest is the bond between the newly formed interlayer of complex oxides and the weld metal. It can be assumed that the strength of this bond is determined to a large degree by the SOSC principle.

In phases that substantially differ in the SOSC principle from the steel weld metal (e.g. titanates MeO·MeO_2) the bond with the latter is violated or becomes weaker immediately after formation of oxides, i.e. at a temperature of about 1100 °C.

Many of the above factors work during the process of cooling of the weld metal, leading to separation of the complex oxide interlayer. Therefore, violation or substantial weakening of the bond between the slag crust and weld metal takes place on the considerable surface area of grains (at a distance from their boundaries). In particular, this applies to the interlayer containing a large amount of phases which differ in their structure from the weld metal. However, the «roots» of the oxide material may be reliably fixed in the grain-boundary valleys as the volume of oxide is always larger than the volume of metal consumed for formation of the oxide, $V_o/V_m > 1$. It is likely that this character of fixation of the slag crust on the surface of the weld metal (practically due to mechanical jamming of the «roots» of an oxide material in the grain-boundary valleys) is an additional cause of poor detachability of the slag crust in welding, independently of the relationship of structural-physical parameters of the metal and complex oxide interlayer.

In a case when the newly formed phase is similar to the weld metal in structure (e.g. spinel

$MeO \cdot Me_2O_3$), the strength of its bond to the metal hardly changes, compared to the strength of the thin oxide film, and remains high. Some mismatch between lattices of the γ-phase and spinels at high temperature can be compensated for with no damage to the bond strength by increase in the degree of imperfection of lattices of both phase within the contact zone.

If the energy of bond of the interlayer to the weld metal is higher than the energy required for the misfit dislocations to occur in the surface metal layer, increase in the dislocation density in a thin layer of the weld metal near the surface of its contact with the slag crust will take place during cooling of this metal layer (as well as during $\alpha \rightarrow \gamma$ transformation) [15]. It is likely that this process compensates for a difference in contraction of the metal and interlayer, as well as for a dramatic change in the lattice parameters in the course of the $\gamma \rightarrow \alpha$ transformation, thus resulting in persistence of the bond between the interlayer and weld metal and causing poor detachability of the crust.

It appears that in the last case the certain combination of peculiarities of a defective structure of the complex oxide film, diffusion and activity of oxygen in the slag and alloying elements in the weld metal, mutual solubility of oxides, and other factors may promote development of the processes competing with formation of spinels at the interface between the slag and weld metal. For example, such a process may be formation of higher oxides of the type of Me_2O_3, the lattice of which differs in the SOSC principle from the weld metal. The latter leads to violation of the initially strong bond of the spinel interlayer to the weld metal, thus improving detachability of the slag crust.

CONCLUSIONS

1. Poor detachability of the slag crust cannot be always explained by using the generally accepted interpretation of the mechanism of chemical adhesion of the slag crust to the weld metal. In particular, the value of structural-size correspondence of the slag and oxide film phases in the weld metal, as well as conditions and role of epitaxial crystallisation of the slag phases require further investigation and clarification.

2. The phase composition of slag may be heterogeneous in height of the slag crust. When comparing the slag and weld metal phases by the SOSC principle, it is necessary to account not for the integrated phase composition of the slag, but for its phase composition on the surface of the slag crust in contact with the weld metal.

3. The mechanism of adhesion of the slag crust to the weld metal can be controlled in the required way by changing strength of the chemical bond between the interlayer and weld metal, thickness and phase composition of the interlayer, which can be achieved by changing chemical composition of the slag and its oxidising potential.

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CONCENTRATIONS OF CARBON OXIDE AND NITROGEN DIOXIDE IN AIR OF A WORKING ZONE IN COVERED-ELECTRODE WELDING

O.G. LEVCHENKO[1], **A.O. LUKIANENKO**[1] and **Yu.O. POLUKAROV**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]NTUU «Kiev Polytechnic Institute», Kiev, Ukraine

The paper presents the results of investigations of dependencies of concentrations of noxious gases (carbon oxide and nitrogen dioxide) released into working zone air in covered-electrode manual arc welding on distance to welding arc under different ventilation conditions (with general ventilation, local ventilation and without ventilation). Respective analytical equations are derived that allow forecasting noxious gas concentrations in different points of the working zone depending on welding arc power.

Keywords: *arc welding, covered electrodes, noxious gases, carbon oxide, nitrogen dioxide, ventilation, concentration of gases in air, prediction*

One of the negative effects of electric-arc process is formation and accumulation of the welding fumes and gases in air of a working zone. Protection of the workers and production environment from their effect is carried out with the help of different types of the ventilation systems which should provide a content of harmful substances in air of the working zone not higher than the maximum allowable concentration (MAC). The experimental data about concentration of the harmful substances in air of the working zone at different types of ventilation are necessary for selection of required ventilation and increase of its efficiency on the work places of welders. Data on investigation of pollution of air in the working zone with harmful substances in a form of fumes, formed in covered-electrode welding (for example, in [1]) exist in literature in sufficiently large amount, but data on noxious gases are absent. This is explained by the fact that obtaining of such data using generally accepted techniques [2, 3] is sufficiently long and labor-consuming task. Thus, sampling of only one gas specimen in one point of airspace of the welder's work zone applying specific grade of welding consumable takes virtually a working shift. At that, a relative error of obtained data should make ±25 % in accordance with requirements [4] that allows providing a selective definition of content of a substance at the level not higher than 0.5 MAC. Today there are no safe gas analyzers which would allow providing a high reliability for definition of their concentration in air of the working zone. Therefore, a necessity has appeared in obtaining of such data through a calculation based on experimental data.

Noxious gases, forming in an arc atmosphere during covered-electrode welding, include carbon oxide, nitrogen dioxide, hydrogen fluoride and ozone. A composition of electrode coating [5] determines to a significant level a composition of forming gases. High-temperature and photochemical oxidation of air nitrogen [6] is mainly the reason for formation of poison nitrogen dioxide. The level of formation of these gases depends on welding arc power.

The aim of the present paper is to investigate the carbon oxide and nitrogen dioxide concentration dependencies in different points of air of the working zone on the welding arc power, distance to welding point (welding arc) and type of ventilation system in low-alloy covered-electrode welding.

The experiments were performed on a typical work place for manual arc welding using general and local ventilation as well as without ventilation in the E.O. Paton Electric Welding Institute. Gas samples were taken around the arc in three points at different distance from the arc: 55 cm (welder's breathing zone), 100 and 150 cm (working zone). A capacity of general as well as local ventilation was selected equal 1500 m^3/h for efficiency comparison. A typical axial-blow blower was used in the general ventilation system and typical welder's table with built-in exhaust device of inclined panel type [1] was applied in the local one.

Gas samples were taken in the process of surfacing with general-purpose covered-electrodes of ANO-36 grade of 4 mm diameter on plates from St3sp (killed) steel. Direct current of reversed polarity was used. The welding current was changed in the ranges from 130 to 230 A, arc voltage made 24–40 V for determining the dependence of concentrations of gases in air of the working zone. Gas analyzer «Akvilon-1-1» was used for definition of carbon oxide CO concentrations in air of the working zone and «Akvilon-1-2» was applied for nitrogen dioxide NO_2. A validity of obtained experimental data was checked in accordance with the accepted procedural instructions [4]. Ana-

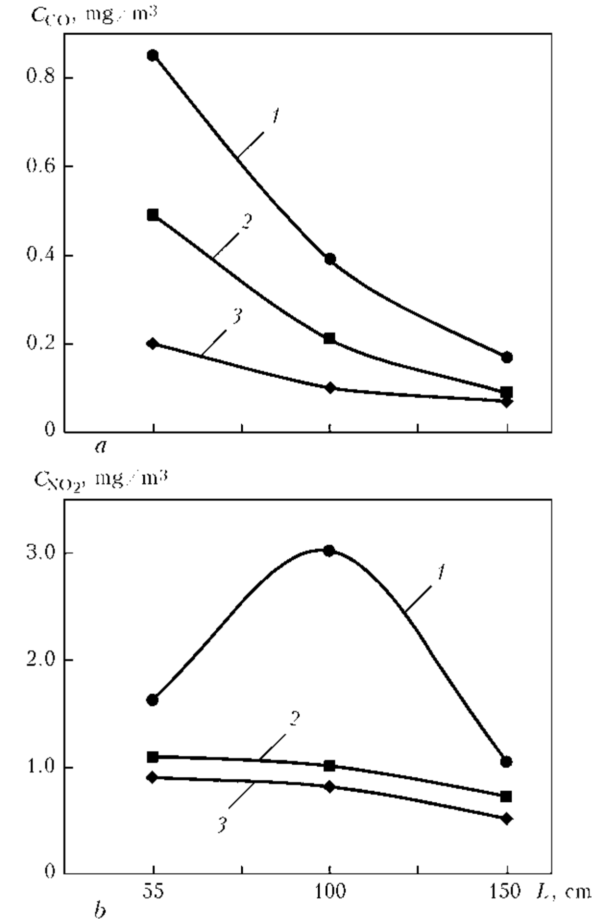

Figure 1. Dependence of carbon oxide C_{CO} (*a*) and nitrogen dioxide C_{NO_2} (*b*) concentration in air of the working zone on distance *L* to the welding arc in welding without ventilation (*1*), with general (*2*) and local (*3*) ventilation

lytic and statistic processing of determined dependencies was carried out using special program, developed in the National RI of Industrial and Occupational Safety, with the help a method of regression analysis [7, 8] underlying in it.

Investigations of carbon oxide concentration dependencies on distance to the welding arc (Figure 1, *a*) indicate that they are maximum in welding without ventilation, minimum at the local ventilation and reduce with an increase of arc distance, but for all cases do not exceed MAC (20 mg/m^3). The reason for formation of carbon oxide during covered-electrode welding is, mainly, the air oxidation of carbon, which is contained in metal and electrode coating, at the first stage:

$$C + O_2 = CO_2,$$

and dissociation of carbon dioxide as a result of high temperature of the welding arc at the second stage:

$$CO_2 \leftrightarrow CO + \frac{1}{2} O_2,$$

as well as metal reduction of carbon from its dioxide,

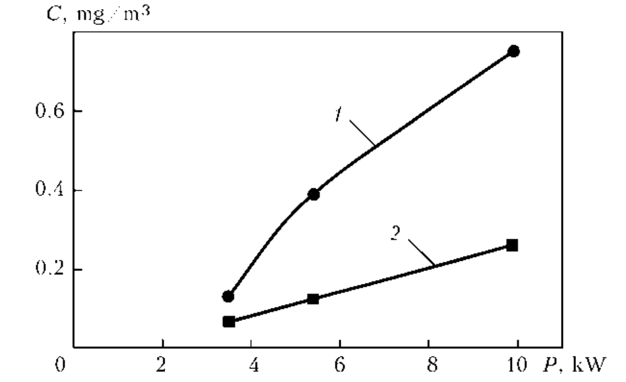

Figure 2. Dependence of carbon oxide (*1*) and nitrogen dioxide (*b*) concentration in air of the working zone on the arc power at 100 cm distance to the welding arc

$$CO_2 + Me = CO + MeO.$$

Besides, a presence of carbon dioxide in ambient air in the amount of 0.03–0.04 % [9] can be a source for formation of carbon oxide in a low quantity. As a result of chemical reaction (2) the carbon dioxide decomposes to the carbon oxide at high temperature of the arc. Therefore, total low concentration of carbon oxide in air of the working zone is explained by insignificant content of carbon in the composition of metal to be welded and ambient air. Carbon oxide is also formed in welding by electrodes with cellulose and carbonate-containing coating as a result of thermal dissociation of these gas-slag-forming components of the coating. In these cases an increased amount of carbon oxide is released in air of the working zone.

Dependencies of nitrogen dioxide concentration in air of the working zone on distance to the welding arc have more complex form, in particular, in welding without ventilation (Figure 1, *b*). This is explained by successive oxidation of air nitrogen in two stages. Firstly, nitrogen oxide appears in the near zone as a result of high-temperature oxidation of air nitrogen, surrounding the arc:

$$N_2 + O_2 \leftrightarrow 2NO,$$

then, nitrogen oxide oxidizes with time and removing from the arc up to poison nitrogen dioxide [6, 10] under the effect of ultraviolet radiation of the arc:

$$2NO + O_2 \leftrightarrow 2NO_2.$$

Therefore, at certain distance from the arc (around 1 m) the concentration of nitrogen dioxide increases due to its accumulation in air in welding without ventilation and decreases at further removal from the arc (up to 1.5 m) due to dispersion.

It should be noted that the concentrations of nitrogen dioxide in the working zone do not exceed MAC (2 mg/m^2) at application of the local as well as general ventilation. In welding without ventilation the concentration of nitrogen dioxide exceeds MAC (see Figure 1, *b*) at a distance from 80 up to 130 cm to the welding arc.

Table 1. Values of the relative errors and total correlation factors of dependencies (1)–(6)

Dependence	Relative error, %	Total correlation factor
(1)	18.0	0.940
(2)	18.2	0.986
(3)	19.2	0.939
(4)	5.0	1.0
(5)	10.0	0.074
(6)	11.5	0.960

An increased content of nitrogen dioxide in the zone near to the welding arc in application of the local as well as general ventilation is explained by more active nitrogen oxidation then in the zone distant from it. This result in formation of larger amount of nitrogen oxides in the breathing zone, and the intensity of oxidation of air nitrogen, naturally, decreases with increase of a distance from the welding arc.

It can be seen from the dependencies of concentrations of carbon oxide and nitrogen dioxide in air of working zone on the welding arc power that the concentrations of these gases in air raise with increase of arc power (Figure 2).

Analytic and statistical processing of determined dependencies (see Figure 1), made with the help of the method of regression analysis [7, 8], taking into account influence of the distance to welding arc and its power (see Figure 2) allowed obtaining the following dependencies:

• dependence of CO concentration (C_{CO}) on power ($I_w U_a$) of the welding arc and distance to arc L (m) in welding

without ventilation:

$$C_{CO} = -0.197 + 2.178\cdot10^{-4} I_w U_a + 0.071L - 1.192\cdot10^{-4} I_w U_a L, \quad (1)$$

with general ventilation:

$$C_{CO} = -48.099\cdot10^{-2} + 2.929\cdot10^{-4} I_w U_a + 34.679\cdot10^{-2} L - 3.268\cdot10^{-4} I_w U_a L + 0.902\cdot10^{-4} I_w U_a L^2, \quad (2)$$

with local ventilation:

$$C_{CO} = -2.657\cdot10^{-2} + 0.439\cdot10^{-4} I_w U_a - 0.857\cdot10^{-2} L - 0.177\cdot10^{-4} I_w U_a L; \quad (3)$$

• dependence of NO_2 concentration on power of the welding arc and distance to arc in welding

without ventilation:

$$C_{NO_2} = -4.991\cdot10^{-2} + 0.414\cdot10^{-4} I_w U_a + 0.942\cdot10^{-2} L - 0.11\cdot10^{-4} I_w U_a L, \quad (4)$$

with general ventilation:

$$C_{NO_2} = 1.344\cdot10^{-2} + 0.209\cdot10^{-4} I_w U_a - 4.014\cdot10^{-2} L, \quad (5)$$

with local ventilation:

$$C_{NO_2} = 2.195\cdot10^{-2} + 0.162\cdot10^{-4} I_w U_a - 4.182\cdot10^{-2} L. \quad (6)$$

The values of relative errors and total correlation factors of determined dependencies are shown in Table 1. As can be seen from the Table, the values of relative errors do not exceed (25 %) value [4] indicated by procedural directives. The total correlation factors of data of dependencies have values from 0.94 to 1.0 (see Table 1) that indicates that obtained mathematical dependencies can be used for calculation of concentration of carbon oxide and nitrogen dioxide in the welder's breathing zone and in the working zone for the purpose of hygiene and sanitary evaluation of the work environment.

Comparison investigations of concentration of these gases in different points of space in welding without ventilation with other known grades of the electrodes were carried out with the aim to check the validity of mathematical dependencies (1)–(6) for other grades of electrodes differing by coating composition. These results showed that the mean concen-

Table 2. Concentration of carbon oxide in air of the working zone

Electrode grade	Distance to welding place L, m		
	0.55	1.00	1.50
	Minimum and maximum allowable concentration CO, mg/m^3		
	0.64–1.06	0.29–0.49	0.13–0.21
ANO-36	0.85	0.39	0.17
ANO-4	0.65	0.43	0.13
ANO-24	0.40	0.22	0.10
UONI-13/55	1.23	0.29	0.50
ANO-6	1.19	0.02	0.73

Table 3. Concentration of nitrogen dioxide in air of the working zone

Electrode grade	Distance to welding place L, m		
	0.55	1.00	1.50
	Minimum and maximum allowable NO_2 concentration, mg/m^3		
	1.22–2.04	2.26–3.78	0.79–1.31
ANO-36	1.63	3.02	1.05
ANO-4	1.56	2.60	1.23
ANO-24	0.85	1.42	1.37
UONI-13/55	2.34	1.58	1.33
ANO-6	2.40	1.78	1.98

trations of determining gases do not exceed the limits of allowable error (25 %) among the electrode grades, indicated in Tables 2 and 3, only in welding with ANO-4 electrodes. Thus, a conclusion can be made that the mathematical dependencies (1)–(6) can be used for prediction of air pollution of the working zone, at least, in welding with rutile and rutile-cellulose covered electrodes.

The results of investigations of carbon oxide and nitrogen dioxide concentration dependencies in manual covered-electrode welding should be taken into account in carrying out the hygiene and sanitary evaluation of the work environment. At that the requirements of GOST 12.1.005–88 [11] should be followed. According to it, a total effect on human organism of unidirectional substances should be taken into account to prevent the possibility of excess of MAC in air of the working zone. Therefore, considering that carbon oxide and nitrogen dioxide have unidirectional general-toxic effect [11] the hygiene evaluation of air in the working zone and selection of ventilation system in this case are to be carried out keeping the following conditions:

$$\frac{C_{CO}}{MAC_{CO}} + \frac{C_{NO_2}}{MAC_{NO_2}} \le 1. \qquad (7)$$

Calculations, obtained on formula (7) based on data of Figure 1, showed that the results of total effect of oxide and nitrogen dioxide can take different values depending on the welding conditions (presence or absence of ventilation), distance to the welding arc and welding mode, i.e. can be more or less than 1, that makes the basis for selection of type and capacity of ventilation.

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ALL-PURPOSE POWER SOURCE FOR ARC WELDING AND PLASMA CUTTING

A.V. VLADIMIROV[1], **V.A. KHABUZOV**[1], **V.A. LEBEDEV**[2], **S.Yu. MAKSIMOV**[2] and **A.A. GALYSHEV**[3]
[1]Laboratory of Electronic Technology, Ltd., St.-Petersburg, Russia
[2]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[3]St.-Petersburg Mechanical Engineering Institute (PIMASh), St.-Petersburg, Russia

A new design of an all-purpose inverter current source is considered for mechanical processes of arc welding and surfacing of steels and aluminium alloys. The source features the capability of fast and controllable setting of many parameters of the welding process and regulation of any appearance of external static volt-ampere characteristics and dynamic properties, as well as realization of pulsed modes in a wide range.

Keywords: *arc welding, plasma cutting, power source, rectifier, inverter, characteristics, software, design*

At present both traditional rectifiers and inverter power sources are used in welding fabrication. Sources with adjustable thyristor-type rectifiers or inadjustable rectifiers will still be in demand in the market for a long time, owing to a comparative simplicity, reliability and relatively low price. They can be used in modern efficient welding processes, for instance in the method of welding with forced short-circuiting (FSC) developed by ITS and SELMA companies (RF–Ukraine) [1]. At present inverter power sources of varying degrees of complexity are ever more intensively introduced into welding fabrication. For sound performance of welding-surfacing operations, achievement of a high efficiency and fulfilling the objectives of energy- and resources saving, the users will select exactly such power sources.

Two tendencies can be outlined in inverter power source design. The first is aimed at lowering of weight and dimensional characteristics of the equipment and improvement of its efficiency [2], and the second tendency is aimed at realization of electrode metal transfer control [3]. The latter of the defined tendencies requires availability of «intelligent» sources that have already been developed, or are being developed and manufactured by various companies now. Their feature consists in the possibility of realization of algorithms of electrode metal transfer control, such as metal transfer by surface tension forces (STT) and cold metal transfer (CMT).

It should be noted that despite the attractiveness of developments of inverter-type power sources using the intellectual potential of their software, the following tasks are still unsolved or only partially solved:

- ensuring reliable enough design solutions on source protection at operation under the real production conditions;
- realization of modular design of power components to ensure a wide range of nominal current values and various levels of output voltage;
- optimization of maintenance, additional programming or reprogramming to obtain qualitatively new processes of welding and surfacing, corresponding to the conditions of modern fabrication, advanced technologies, etc.

The purpose of this work is to familiarize welding fabrication specialists with the development made by Laboratory of Electronic Technology, Ltd. (St.-Petersburg, RF) with technical and consultational assistance of PWI experts.

The presented development is based on the principle of separation of the power and information components of the power source, ensuring the versatility and high level of equipment unification, and also allowing solution of a number of problems related to control of arc processes in welding and cutting.

Versatility is considered in several aspects: possibility of conducting a number of processes of welding and surfacing, as well as achievement of effective control of the process of welding or surfacing. For instance, in mechanized welding with short-circuiting (SC) electrode metal transfer with minimum level of its losses and sound weld formation can be ensured. Rather important in terms of power source versatility is ensuring its operation under diverse production conditions. In arc and plasma-arc processes of welding availability of a wide range of welding current (I_w = = 10–1500 A) and arc voltage (U_a = 16–260 V) values is required.

The simplest way to create all-purpose equipment for welding is development of a powerful source providing the required range of values of welding current and voltage for cutting. For the majority of users such a power source will be redundant in terms of its components and realized characteristics. Moreover, it will be expensive and, therefore, will not have the anticipated wide application.

For this reason, in the considered study the goal of equipment versatility is achieved by application of one typical power functionally complete block — module with minimum required parameters, which provides high values of efficiency, reliability, as well as the required load and dynamic characteristics.

Module control is numerical and envisages mounting power-independent storage in equipment for storing welding programs and parameters of power source setting up.

Each module is made so that the radiators of its power keys are located inside the module, and all the electronic components are outside. With such an arrangement air passes through the module, without contacting the electronics, or contaminating it. This is particularly urgent for real operation conditions (high dust level, presence of an electrically-conducting medium, etc.). A variant of mounting the source into a plastic waterproof case was developed that can be effectively used in development of a new set of equipment for underwater arc welding and cutting of metals by a consumable electrode. Selection of power characteristics of the source (current and voltage) is performed by parallel (in welding) and in series (at certain modes of welding and cutting) connection of the modules. Organization of the power source external characteristics required for the welding process and their no-failure operation are achieved using a special computer program.

Developed control system provides at power source output the dynamic and volt-ampere characteristics (VAC) required for each welding process. Control system determines many conditions of current and voltage that may be realized in operation. A clear and convenient interface for entering and correction of power source characteristics is important here.

We will demonstrate the operation of power source control system in the case of graphic design of external VAC. VAC are usually presented in the form of curves which at crossing the axes determine SC current and open-circuit voltage. There exists a multitude of them and user base can be compiled, if required by the customer.

VAC of welding current power source determine in many respects the possibility of realization of the welding process, its quality [4], and even the ability to ensure a certain type of electrode metal transfer, as, for instance, the above-mentioned process with FSC. The universally accepted form of VAC presentation is the graph. Therefore, entering and correction of VAC were realized in the graphic form by a special editor on PC, connected to power source through USB interface.

A specially developed graphic editor allows drawing the required VAC on the computer screen, and then sending it for execution to the system. View of editor program screen and VAC curves are shown in Figure 1. VAC entering in most of the cases is required

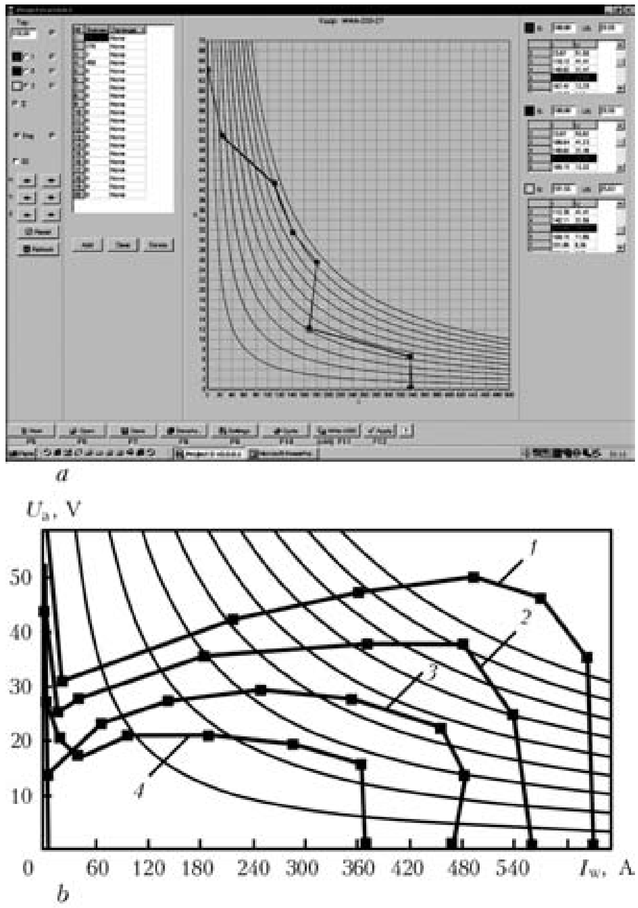

Figure 1. View of editor program screen for entering VAC into power source (*a*) and VAC curves generated in mechanized welding in different modes (*b*): *1* — $I_w > 250$; *2* — 150–250; *3* — 100–150; *4* — 50–150 A

for total setting up of the system under the conditions of production and initial programming, as well as for research and technological practice that we believe to be the most important. Source memory allows storing hundreds of VAC, and the welder just has to select the most suitable of them for specific welding conditions, welding consumables and modes.

It is known [5] that consumable electrode arc welding is a complex dynamic process that includes both fast (for instance, drop formation and transfer), and long-term (for instance, weld formation) processes. Sound performance of welding requires equally good control of these processes at any stage of their running. Different duration of welding processes also requires different methods of their control.

Importance of the source dynamic characteristic consists in ensuring the speed and nature of power source response to introduction of a disturbance into the load (change of load). Classic solution consists in application of throttles which regulated the speed of current rise and drop in the welding circuit by changing the load inductance. Throttle application is inconvenient, as adjustment of their inductance should be step-like, requiring turning the system off for switching. In the majority of new developments of welding current power sources of the known companies (for instance, realisation of QSet function — realisation of optimal SC frequency for the given combination of gas/wire in the most recent development by Swedish concern ESAB), the required speeds of current rise and drop are achieved using electronic devices, so-called electronic throttles.

In most of the cases, duration of current rise (drop) in welding is equal to approximately several milliseconds. In the development considered by us, such tasks are solved also by application of programmable electronic means. Here the energy capabilities of the module allow reaching maximum values of welding current by an order of magnitude faster. Therefore, the control system even for the fastest response to introduction of disturbances should «decelerate» the module, lowering the fast rate of current rise. This can be done, for instance, by the control system issuing every 0.1 ms the commands for current increase by 10 % of the sought value. Thus, the rate of current rise is changed, and the required dynamic characteristics of the power source are generated in the ranges required for welding and cutting.

In the power source, in which dynamic and VAC output characteristics are adjusted in a rather simple way, any of the known algorithms of electrode metal transfer control can be realised, that, as follows from analysis of welding equipment of the known manufacturers, is a priority task, solution of which ensures a sound and efficient running of the welding processes. Note that several new control algorithms were generated at validation of the system of graphic design of welding process characteristics, including on-line regulation of the fronts of pulse rise and decrease, as well as simultaneous control of the power source and drive of electrode wire pulsed feed [6]. The latter solution, in our opinion, is one of the directions of further improvement of welding current power source and equipment sets for mechanized and automatic welding as a whole.

Figure 2. Variant of design of welding current source LET 350 with metallic sheath and touch-type display

At present practically all the levels of control of welding processes and methods of their implementation have been developed. All the known control algorithms of the pulsed-arc process with a wide range of parameters of variable characteristics (level, pulse repetition rate, frequency and pulse shape) have been verified in the power source [7].

Control system of the power source contains built-in sensors of current and voltage that are used both to solve the internal tasks related to control of arc process parameters and to transfer information to external devices.

All the capabilities of the power source control system are provided by digital processing of the current state so that it can be called complete numerical control of the welding process (NCWP). Here it is appropriate to apply such a concept as graphic design of power source characteristics for any possible arc welding process with those parameters that the technologists believe to be necessary and the most effective.

For convenience the power source control panel incorporates a graphic display that is used to implement various intuitively understood algorithms of control and monitoring by a special program.

Two important features of the new development can be also noted. Upgrading of the currently available and mastering new welding technologies are essentially simplified, as it is possible to select VAC and dynamic characteristics of the power source in the laboratory at a sufficiently high level. These characteristics can be sent through the Internet or by mail for entering into any power source. As shown by experience, their incorporation into the currently available production systems does not involve any difficulties. Another advantage of the new development that, however, is not so far realized by the local users in welding, is the possibility of remote objective monitoring of welded joint performance. This is achieved by two methods: either the power source records into its memory all the process parameters, and then archives the report about work performed, or sends them to a special server, performing monitoring and recording of work performed.

Note that by agreement with the customer the power source can have gas cut-off valve and adjustable d.c. electric drives for electrode wire feed mechanism with the necessary elements of their programmed switching on by the welding cycle.

During evaluation of the capabilities of the new development, specialists of «Laboratory of Electronic Technology» and PWI for several work days performed a series of studies on LET 350 power source (Figure 2) with standard feed mechanism of PDGO-510 type with its torch fastened in the welding carriage slot, with variation of VAC, dynamic characteristics of the power source, as well as with application of pulsed impacts, etc. All the power source parameters

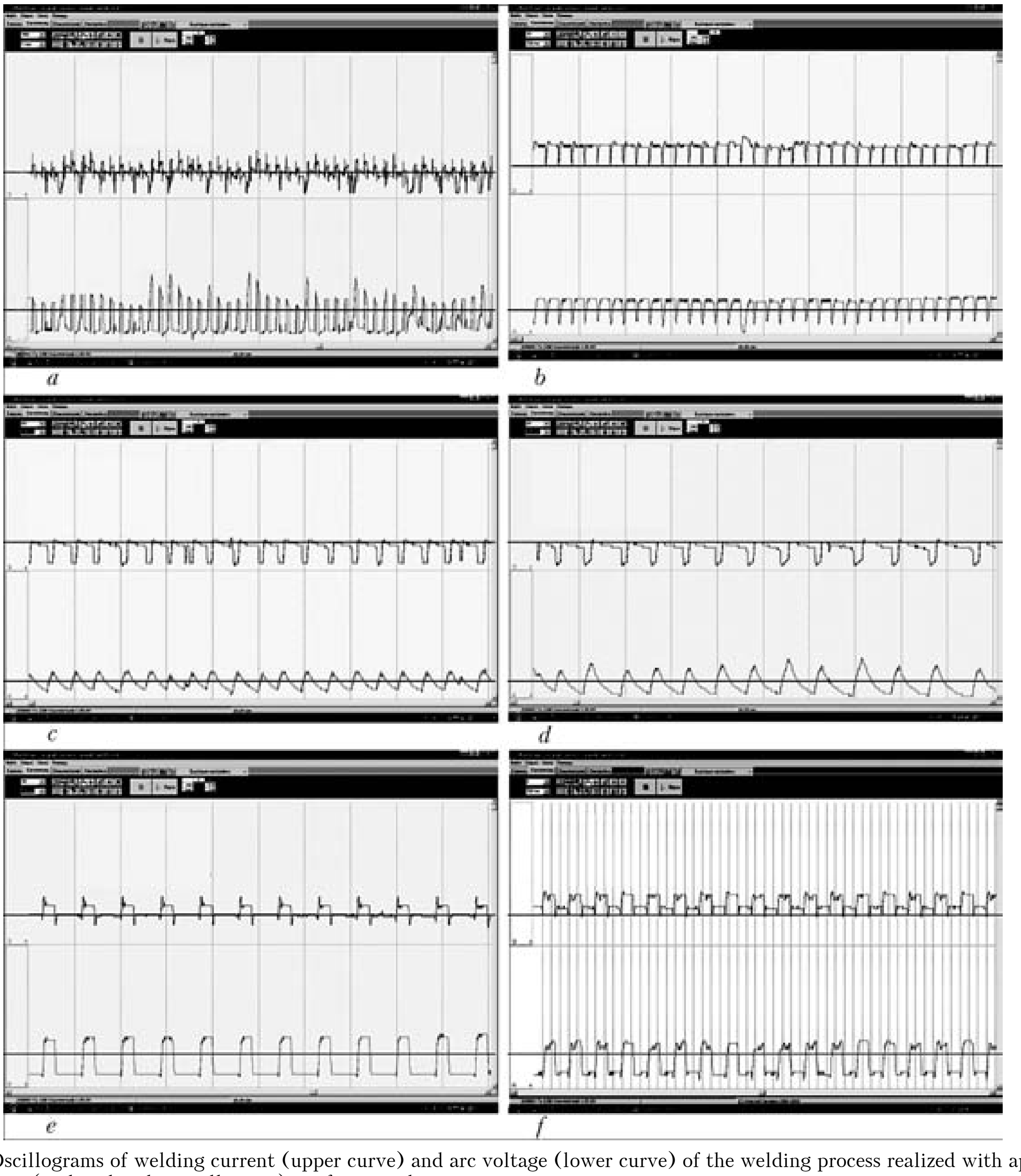

Figure 3. Oscillograms of welding current (upper curve) and arc voltage (lower curve) of the welding process realized with application of LET source (scale taken by oscillogram): *a*–*f* — see the text

were set in on-line mode and were evaluated by quality of deposited metal beads, oscillograms of current and voltage. Electrode wire Sv-08G2S of 1.2 mm diameter was used. Carbon dioxide gas was the shielding medium. The main modes were selected by recommendations of [4].

Let us consider several variants of welding processes as an example. Welding was performed at welding current of 90–140 A and arc voltage of 18–24 V. Figure 3, *a* shows welding process oscillogram with a relatively small value of inductance in the welding circuit (lees than 0.1 mH) at uniform rigid VAC and absence of the pulsed mode of power source operation. Arc voltage value was on the lower limit of the recommended range. It is seen that the welding process was running with SC, electrode metal transfer process being quite chaotic. At increase of the inductance, the welding process in terms of transfer is ordered and stabilized. Here the arcing and SC periods can be precisely recorded, as is readily seen in Figure 3, *b*. Then, with increase of welding circuit inductance SC frequency decreases and cycle pulse repletion rate changes that can be traced by oscillograms in Figure 3, *b*–*d*. This enables regulation of heat inputs into the weld pool due to programmed variation of inductance. Oscillograms in Figure 3, *e*, *f* also demonstrate the possibility of controlling electrode metal transfer through application of various VAC of the power source and of a pulsed component of voltage with parameters close to those of natural transfer. In this case, welding was performed at a combined VAC of the type presented in Figure 4, while changing parameters *A*, *B* and *C*. The Figure also shows changes of transfer cycle pulse repetition rate.

Thus, it is obvious that changing two parameters of welding current power source (time constant of

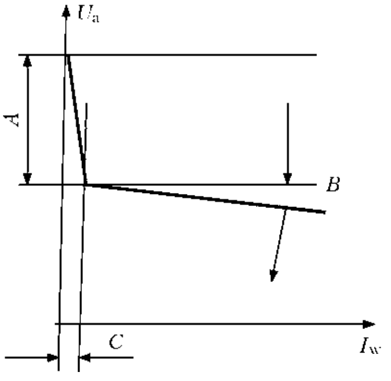

Figure 4. Combined VAC of welding current source: A — open-circuit voltage of welding current source; B — rigidity of external VAC; C — zone of higher voltage action

welding circuit at the expense of dynamic characteristics and VAC shape) by certain algorithms enables essentially influencing electrode metal transfer, stabilizing it and monitoring its energy characteristics, and, therefore, also influencing the coefficient of electrode melting and base metal penetration.

By now a program has been put together for investigation of the capabilities provided by the design of LET power source and programming system. At the first stage of investigations it is intended to determine the influence of inductance, VAC, pulsed algorithms on the welding process and welded joint formation, and in the second stage — that of various feedback structures and application of force impacts on electrode metal transfer.

CONCLUSIONS

1. NCWP provides quality setting up of equipment for specific operation, fast reproduction of settings and their repeatability. The main advantage of development of Laboratory of Electronic Technology, Ltd. [8] is provision of welded joint quality based on the principles of numerical synthesis of the welding process.

2. Realisation of the concept of a versatile system for welding and cutting with NCWP simplifies and makes less expensive the well-established systems of design, production and operation of welding equipment, thus providing a high welding quality.

3. Versatility of power sources is cost-effective for large-scale productions, operating hundreds of welding systems of various purposes and power due to simplification of their operation and possibility of manoeuvring from one site to another, and one welding process to another. Operation of equipment of one type consisting of several typical modules, is much simpler and more inexpensive that that of different equipment from various manufacturers [9].

4. The future of welding and cutting consists exactly in NCWP application. Welding productions that start applying the above principles earlier will gain a natural advantage over their competitors in terms of the cost and quality of their products.

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STATE-OF-THE-ART OF DEVELOPMENT AND MANUFACTURE OF LOW-HYDROGEN ELECTRODES WITH DOUBLE-LAYER COATING IN CIS COUNTRIES (Review)

A.E. MARCHENKO[1], **N.V. SKORINA**[1] and **V.P. KOSTYUCHENKO**[2]
[1]E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine
[2]OJSC «Mezhgosmetiz-Mtsensk», Oryol, Russia

The article gives generalised information on properties of low-hydrogen electrodes with a double-layer coating, as well as characteristics of metal of the welds made by using the above electrodes, including electrodes of the ANOD-1 grade, the technology of manufacture of which is oriented to the available feedstock.

Keywords: *arc welding, welding electrodes, double-layer coatings, development, manufacture*

Double-layer coating is one of the most effective means for increasing welding-processing characteristics of the electrodes with basic coating. In it a calcium fluoride, one of the main arc deionizer, is removed in peripheral layers [1]. An outer layer of the coating, isolated from main, high-temperature arc region, experiences an overheating in a smaller degree, its constituents have less intensive evaporation and dissociation, and influence on composition of arc atmosphere to a smaller extent. Namely this part of the coating flows into a weld pool and has less interaction with drop at the end of the electrode [2]. Removing of the fluorides outside the boundaries of inner layer reduces the possibility of occurrence of exothermal hardphase reactions in this layer of the coating. It mainly contains reactions of carbonate dissociation. They, being endothermic by nature, «subcool» a core, changing surface profile from convex to concave one that reduces a danger of drop yield outside the boundaries of a cap of non-melted coating and possibility of short circuits.

Studies [3–5] show that an application of the electrodes with double-layer coating provides a fine-drop electrode metal transfer as well as good formation and quality of weld metal including in low current welding. The latter has great importance in erection welding as well as using the electrodes with cores from high-alloy wire when an allowable welding current is often limited for preventing core overheating and reduction of heat input in the weld pool. Therefore, some electrodes, designed for welding of high-alloy steels, also have the double-layer coating.

Application of the double-layer coating allows increasing stability of arcing during welding at alternating current in using of the transformers with low open-circuit voltage [6].

The first known patent for the electrodes with double-layer coating appeared in Czechoslovakia [7]. The compositions of coatings and method for manufacture of the double-layer electrodes using simple presses were patented in Finland, Switzerland and Norway [8–10]. A technology of manufacture of the double-layer electrodes on the direct-flow presses [11] was patented by «Oerlikon» company. There are patents for the coated electrodes number of layers in which exceeds two [10, 12] or being operated from two current sources [13, 14].

Double-layer structure of the coating extends technological capabilities for regulation of efficiency, welding-processing characteristics of the electrodes, indices of arcing stability, chemical composition and mechanical properties of deposited metal, etc. For that, a distribution of constituents of the coating between the outer and inner layers and change of section area ratios of inner and outer layers, which judging on the patents and information data can vary in the ranges from 1:1 to 2:1 depending on solved tasks, are added to the tradition ways, based on changing of substantial composition of the coating.

The electrodes with double-layer coating are widely used in industry and building of many countries. Companies from Switzerland (Oerlikon), Sweden (ESAB), Japan (Kobe Steel), Austria (Boehler), Germany (Thyssen Draht, UTP), the Netherlands (Philips), USA (Selelectrode) and etc. organized manufacture of the electrodes with double-layer coating at different times. Oerlikon obtained among the first a patent for composition of the coating and method for manufacture of the electrodes with double-layer coating on direct-flow presses [11]. It manufactured almost 50 % of low-hydrogen electrodes with double-layer structure of the coating from total output of the electrodes of main type on their enterprise in Eisenberg (Germany).

Catalogue of Oerlikon shows 19 grades of double-layer electrodes of different designation (Tables 1–3). The low-hydrogen electrodes of general designation as well as designed for welding of high-strength, heat-

Table 1. Specification of the electrodes with double-layer coating according to the catalogue of «Oerlikon» company designed for welding of low-carbon and low-alloy steels

Electrode grade	Diameter, mm	Code		Mechanical properties of the weld				
		on EN ISO 2560	on AWS 5.1	σ_y, MPa, not more than	σ_t, MPa	δ_5, %, not more than	KVC, J/cm^2, at T, °C	
							+20	−60
Extra	2.5–6.0	E424 B32 H10	E7016	420	500–640	20	150	90**
Spezial	2.0–6.0	E382 B12 H10	E7016	380	470–600	20	150	100*
Tenax 50	2.5–5.0	E426 B32 H5	E7016-1	420	500–640	20	250	100
Tenacito	2.5–6.0	E426 B32 H5	E7016-1	420	500–640	20	180	70
Tenacito 38R	2.5–6.0	E466 1Ni B42 H5	E7018-G	460	530–680	20	190	70
Tenacito 65	2.5–6.0	–	E9018-G	560	630–720	20	160	70
Tenacito 65R	2.5–6.0	E506 1NiMo B42 H5	E9018-G	510	620–720	20	170	55
Tenacito 70	2.5–5.0	E506 1Ni B42 H5	E8018-G	510	590–690	23	200	60
Tenacito 70B	2.5–5.0	E466 2Ni B42 H5	E8018-G1	480	550–700	22	170	100
Tenacito 75	2.5–6.0	–	E11018-G	700	780–940	17	120	55
Tenacito 80	2.5–6.0	–	E11018-G	700	800–960	16	120	60
Tenacito 100	2.5–5.0	–	E12018-G	890	980–1080	14	70	60***
BOR-SP6	4.0–6.0	E506 B34 H10	–	460	530–680	18	160	60

*, **, *** — data given on impact energy relate to test temperatures −20, −30 and −40 °C, respectively.

Table 2. Specification of double-layer electrodes of «Oerlikon» company designed for welding of heat-resistant alloy steels

Electrode grade	Type on DIN 8575	T_{exp}, °C	Content in deposited metal, %				
			C	Si	Mn	Cr	Mo
Molycord Kb	EMoB20+	550	0.06	0.5	0.8	–	0.5
Cromocord Kb	ECrMo1B20+	570	0.06	0.6	0.8	1.0	0.5
Citochrom 2	ECrMo2B26+	600	0.06	0.5	0.8	2.4	1.0

resistant and stainless steels are represented in this list. A complex of methods for deoxidation and alloying of deposited metal was realized in series of developments at which the maximum yield of acicular ferrite in the structure of deposited metal is provided and exclusively high impact toughness of welds at negative temperatures (investigations made by G. Evans) is achieved.

The oerlikon double-layer electrodes are used for welding and repair of such objects of nuclear-power engineering as containment building of reactor (Tenacito 60, 65R, 70, Extra), reactor shell, steam generator and main pump (Tenacito 65R).

Electrodes with double-layer coating are used in power engineering, oil and power machine building, etc. This, as a rule, the electrodes of small diameter and it is very important to have contracted, rigidly oriented in space arc as well as good root penetration when using them for welding. There are exceptions when double-layer structure of the coating is used for electrodes of all diameters (from 2.0 up to 6.0 mm).

The grades of electrodes with double-layer coating, supplied on market by European companies, including ones that do not have press equipment allowing realization of the method of manufacture patented by «Oerlikon» company, are shown in Table 4. These compa-

Table 3. Specification of double-layer electrodes of «Oerlikon» company designed for welding of high-alloy stainless steels

Electrode grade	Type on DIN 8575	T_{exp}, °C	Content in deposited metal, %					
			C	Si	Mn	Cr	Ni	Nb
Basinox 308L	E199L B20+	350 (800*)	0.03	0.4	1.0	19.0	10.0	–
Basinox 347	E199Nb B20+	400 (800*)	0.03	0.4	1.0	19.0	10.0	0.4
Basinox 326 L	E19123L B20+	400	0.03	0.4	1.0	18.5	11.5	(2.7Mo)

*Temperature up to which formation of scale is not observed.

nies use the method of double coating: firstly on a core (inner layer) and then on preliminary dried electrode with inner layer (outer layer) [8, 9].

The following principles are used in development of the electrodes of Tenacito series [15]:

- proved alloying systems based on extensive technological database, now accepted for whole series;
- optimizing of deoxidation system for the purpose of achieving suitable inclusion morphology, and, respectively, obtaining of maximum high level of cleaning and impact toughness of deposited metal;
- extremely high cleanliness of rimmed carbon-manganese steel for electrode rods at rigid control of the level of impurity elements;
- careful selection of mineral constituent of the coating with the purpose of achieving of the necessary level of its basicity for E XX18 type electrodes;
- special binding agent for minimizing hygrosorption capacity of the coating for the purpose of achieving as low content of hydrogen in the deposited metal as possible (not more than 0.2 % of adsorbed H_2O during nine hours exposure of the electrodes in atmosphere with 80 % relative humidity of air at 27 °C);
- optimizing of operating characteristics of the electrodes in root pass welding of multilayer welds by using electrodes of 3.25 mm diameter and less.

Low-hydrogen electrode of general designation with double-layer coating of ANO-D type (E50A type on GOST 9467–75) [16, 17] was developed in the E.O. Paton Electric Welding Institute in 1970s. A modification — electrodes ANO-Ds [18, 19], designed for welding of shipbuilding parts, was developed on its basis. The technology was developed for industrial manufacture of the electrodes with double-layer coating for plants completed with the direct-flow extruding presses. Industrial lots of new electrodes were produced and tested at Rostov research plant «SPA Atomkotlomash» of the Ministry of Power Machine Building and Nikolaev plant «Okean» of the Ministry of Shipbuilding Industry of the USSR. The advantages of ANO-D electrodes over UONI-13/55 electrodes and other grades of similar designation were confirmed by tests. ANO-D and ANO-Ds electrodes were certified for welding of critical parts of NPP from 22K steel as well as ship structures according to the results of tests by Gosgortekhnadzor and Marine Shipping Register.

Unique components, i.e. synthetic mica ANS-1 and low-silicon granulated ferrosilicium of Fs-15gs grade,

Table 4. Grades of the double-layer electrodes manufactured by companies, which do not have direct-flow presses

Company	Electrode grade	Diameter, mm	Code on EN 499	Code on AWS 5.1
ESAB	OK 53.05	2.5–4.0	E424 B22 H10	E7016
	OK 53.16	2.5–4.0	E382 B32 H10	E7016
Thyssen Draht	Phoenix Spezial D	2.5–5.0	E423 B12 H10	E7016
Boehler	Fox EV 50A	2.5–6.0	E423 B12 H10	E7016
UTP	Spezial Z	2.5–5.0	–	E7016
Selelectrode	1162	2.5–5.0	E382 B12	E7016

were used in the coating of electrodes ANO-D and ANO-Ds. This allowed solving the key problems of technology of their conveyer production. These types of raw materials are not manufactured at present time.

In this connection the composition of coating of these electrodes was modernized with orientation towards available types of raw materials as well as widening of sphere of their application taking into account production experience and application of the double-layer electrodes in our country and abroad. Modernized in such a way the electrodes of ANOD-1 grade belonging to E50A type on GOST 9467–75 are meant for welding of structures from carbon and low-alloy steels. Welding is performed in all spatial positions except for vertical-down welds. Direct current of any polarity or alternating current from power sources with open-circuit voltage more than 65 V is used.

Reference designation of ANOD-1 electrodes on DSTU ISO 2560 is A E424 B22 or A E424 B22 H10 depending on electrode diameter [20].

Typical indices of melting of ANOD-1 electrodes are shown in Table 5, and content of gases in the deposited metal in — Table 6.

As follows from data given in Table 6, ANOD-1 electrodes are characterized by fine drop electrode metal transfer and its secure protection from ambient air. They have sufficiently low nominal U_n and, what is very important, considerably high threshold U_{th} arc voltage, achievement of which in the process of arc extension results in formation of pores in the weld. Thus, for electrodes UONI-13/55, arc voltage can be

Table 5. Typical indices of melting of ANOD-1 electrodes

Core diameter to coating diameter ratio, mm	Coefficient of coating mass, %	Coefficient of deposition, g/(A·h)	Efficiency of deposition, h/min	Yield of deposited metal, %
3.0/5.2	60.9; 61.5; 61.9 / 61.4	9.6; 9.9; 9.9 / 9.8	19.3; 19.6; 19.8 / 19.6	109.2; 110.2; 110.4 / 109.9
4.0/6.8	55.5; 56.5; 56.5 / 56.2	9.5; 9.6; 9.7 / 9.6	28.2; 29.0; 29.0 / 28.7	104.9; 106.5; 107.9 / 106.4

Table 6. Arc voltage, at which pores in the weld metal is formed in relation with gas content and characteristics of electrode metal transfer

Electrode grade (diameter, mm)	Content of gases in the deposited metal, %			$\tau_{s.c}$, ms	U_n/U_{th}, V	$\frac{U_{th}-U_n}{U_n}$, %
	$[H]_{total}$	[N]	[O]			
UONI-13/55 (3.0)	4.7	0.022	0.043	3.6	21.5/25.5	18.6
TsL-39 (2.5)	4.8	0.018	0.040	3.2	23.0/29.5	28.2
TsU-5 (2.5)	5.4	0.014	0.039	2.7	23.5/30.0	27.7
ANOD-1 (2.5)	3.9	0.013	0.037	2.3	21.5/30.0	39.5
ANOD-1 (3.0)	4.5	0.016	0.034	2.2	22.0/31.0	40.9

Notes. 1. Content of diffusion hydrogen (in milliliters per 100 g of molten metal), determined by chromatographic method [21], provides data, comparable with index of mercury method of IIW. 2. Contents of oxygen, nitrogen and residual hydrogen were determined by method of vacuum melting. 3. Average statistical time of short circuits was determined by TX-5000 device in downhand short circuit welding.

increased only by 18 % when extending the arc without a danger of porosity formation. TsU-5 and TsL-39 electrodes, designed specially for heat-power engineering, allow extending the arc without porosity occurrence until the arc voltage will not increase by a third in comparison with their nominal voltage. This index makes 40 % for ANOD-1 electrodes.

The results of evaluation, made in a laboratory of the Ministry of Health of Ukraine, for hygiene and sanitary properties of ANOD-1 electrodes, including calculated indices of intensity of air exchange, providing safe concentration of harmful substances in welder's breathing zone, are the following: emission of welding fume particulate matter (WFPM) — 17.0 g/kg and 0.64 g/min; specific emission of fluoric compounds — 0.83 g/kg of soluble and 1.37 g/kg of low-soluble fluorides; specific emission of manganese — 0.78 g/kg. Class on recommended intensity of air exchange (NHL) is 1 (3000 m^3/h); maximum allowable concentration of WFPM in welder's breathing zone — 4.5 mg/m^2; intensity of WFPM emission — 40 g/h.

Technology for industrial manufacture of ANOD-1 electrodes on direct-flow presses of «Oerlikon» company was mastered by OJSC «Mezhgosmetiz-Mtsensk». Two-position briquetting press was developed, manufactured and adjusted: a briquette for inner layer is pressed on one position and for outer layer on another. The double-layer briquette, which is put in a working cylinder of extruding machine, is obtained through inserting one blank into another.

All methods for providing technological and operational characteristics of electrodes and weld metal properties, which are used in manufacture of low-hydrogen electrodes with traditional coating structure, can be used during manufacture of the double-layer electrodes in the scope of mastered technology.

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DEVICES FOR IMPACT TREATMENT OF A WELD IN THE PROCESS OF RESISTANCE SPOT WELDING

A.S. PISMENNY, I.V. PENTEGOV, V.M. KISLITSYN, E.M. STEMKOVSKY and **D.A. SHEJKOVSKY**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Variants of suspensions of welding electrodes for thermomechanical treatment of the weld metal directly during the welding process are considered. Design of the welding head with impact application of the compression force and a variant of the cyclogram for practical implementation of the thin metal welding process are offered.

Keywords: *resistance spot welding, structural steels, weld metal, impact loading, compression force, peening device, welding process cyclogram*

The results of experiments on qualitative estimation of effect of thermomechanical treatment of a weld, carried out directly during welding process, on the strength of welded joint described in [1] show the challenging application of high-speed (impact) compression force at the stage of cooling the metal of a weld spot.

The metallographic analysis of welds shows that impact influence on the metal of a weld spot directly in the process of resistance spot welding results in considerable refinement of microstructure and increase of mechanical strength of welded joints. Especially noticeable is the increase of strength properties in case of multiple application of impact compression force, which is most probably connected with impact influence on weld metal within the certain temperature range. The latter is achieved in the certain period of time which is set with insufficient level of accuracy due to imperfection of applied equipment for measuring temperature of a weld spot in continuous heating of less than ten half-periods of alternating current.

The purpose of this work is to select the optimal variant of a device for impact treatment of weld metal in the process of resistance spot welding.

Basing on results of strength tests of welded and brazed joints produced in gas flame heating and heating using electric resistance, it was established that the method of heating is not a distinctive factor in increase of mechanical strength. The basic parameters influencing the formation of fine-crystalline structure of a weld spot are the temperature range of weld metal duration at the moment of application of impact compression force and quantity of impact pulses.

The topicality of carrying out investigations of welding method with thermomechanical treatment of a weld directly during welding process is seen in the possibility of application of this technological procedure in the processes of joining the structures of thin-sheet metal and such materials for which application of conventional welding methods is impossible. The idea of metal peening in the process of its joining has been already known from the methods of forge welding, but in the variants of its application now the advantages of impact and repeated application of forging force at heating temperature of metals being joined, close to the temperature of their melting, are missed.

It is known that during impact treatment of materials the absorption of impact energy in the regions of heterogeneities of crystalline structure results in increase of level of compression stresses almost twice. The additional evolution of energy at the regions of contact of metals being joined intensifies the processes of mutual diffusion through the contact surface and accelerates the migration capability of atoms of metal in the regions of increased level of mechanical stresses [2–4].

High-speed deformation of metal is accompanied by cold working, the level of which is characterized by impact energy realized for refining the coarse polycrystalline grains of metal and forming the more homogeneous fine-crystalline structure similar to the structure of base metal [5, 6].

Thermomechanical treatment of weld metal directly in welding process is mainly used in the processes of resistance spot welding with a cycle of «peening» [7, 8]. However, the lag effect of pneumatic systems of movement of welding electrode prejudices not only the possibility of practical realization of «peening» of a weld spot, but leads to considerable and undesirable deviations of compression force in the process of a weld spot formation. It is explained by the fact that in the beginning of a heating cycle due to lag effect of a unit of electrode movement the increase of compression force is formed in the zone of a joint of parts due to sharp expansion of metal during heating, and then the electrode «hangs up» and does not manage to experience the almost sudden decrease of metal strength at the moment of its melting, thus promoting the formation of defects of welded joints and deterioration of strength characteristics of a welded joint.

To decrease the lag effect of a unit of electrode movement, the multilink system of electrode fastening

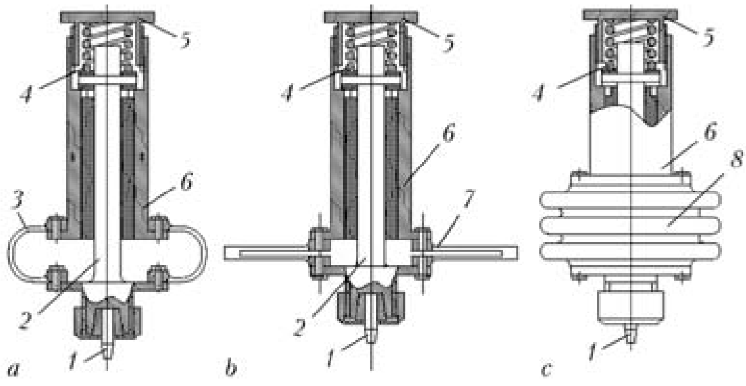

Figure 1. Diagrams of variants of lag effect of suspension of welding electrode: *a* — spring type; *b* — electrodynamic type; *c* — using electrohydraulic effect; *1* — electrode; *2* — moving part of suspension; *3*, *7* — respectively flexible and elastic current connectors; *4* — spring; *5* — controller of preliminary compression force; *6* — body of welding head; *8* — bellows

[9], for example, by arrangement of additional moving element with a lower weight at the lower end of a rod of pneumatic cylinder, which is connected with a rod by a spring-type suspension (Figure 1, *a*), or electrode unit using electrodynamic, electromagnetic forces, electrohydraulic effect and other types of energy transformation, are usually used.

In the suspension of an electrodynamic type (Figure 1, *b*) the electric current passes through two current-carrying surfaces, arranged at minimal distance perpendicularly to the axis of electrode which causes formation of electrodynamic forces in them, forming additional compression force, value and time of influence of which coincide with the shape of a welding pulse.

The considerable increase of impact pressure of compression can be achieved using electrohydraulic effect, for example, as a result of influence of high-voltage electric charge between electrodes submerged into any liquid in the bellows (Figure 1, *c*) [10].

The analysis of advantages and disadvantages of considered variants of design of electrode unit shows that system with an electrodynamic variant of applying impact compression force is more preferable as compared to the system of spring suspension of electrode, as far as the possibility of expansion of range of compression force and synchronization of compression force pulse with welding current pulse appears.

As compared to the system of electrodynamic type the electrode unit of electromagnetic system allows presetting the lag of switching on of pulse of impact influence relatively the welding current pulse, thus to carry out the thermomechanical treatment of weld metal at the preset heating temperature.

One of the advantages of electrode unit with use of electrohydraulic effect is possibility to apply higher speed of additional compression force which should be accompanied by formation of new technological effects. However at the first stage of performance of experimental technological works to confirm revealed advantages of impact thermomechanical treatment directly in the welding process of metals the scheme with electromagnetic application of impact compression force was selected allowing reduction of costs and terms of manufacturing electrode unit.

Therefore, the laboratory installation for performance of investigations of influence of thermomechanical treatment on the properties of weld was additionally equipped with the following units: welding transformer, welding head with unit of application of preliminary and impact compression force, command device and mechanism of movement of welding head (or sheets being welded) for the required distance between weld spots.

The main functions of the command device include providing the sequence of performing the following stages of realization of welding process: switching on of a preset amount of welding current periods; switching on of pulses of impact compression force after the moment of termination of heating pulses (after some time of welding current switching off); switching on of mechanism of movement of welding head or welding table with fastened parts being welded on it for a preset distance.

The design scheme of the unit of impact application of compression effort is presented in Figure 2. As is seen from the cyclogram, switching on of heating pulses of specimens being welded occurs after applying preliminary compression force P_1 to them, the value of which is controlled by variation of distance A_1 of spring compression *3*.

The influence of pulses of impact applying of compression force P_2 occurs within the preset time range t_1 after the moment of termination of heating. The number of pulses of impact application of compression force is defined by the time range t_2 preset by the command device and lag effect of moving part of the electrode unit.

The energy of pulses of impact compression is corrected by setting a gap A_2 between the edge of a solenoid core and a rod with a collet of the welding electrode fixation.

The selection of time moment t_1 is of paramount importance as far as efficiency of application of pulses of impact compression force is decreased both at its minimal value (i.e. at temperature of weld spot close

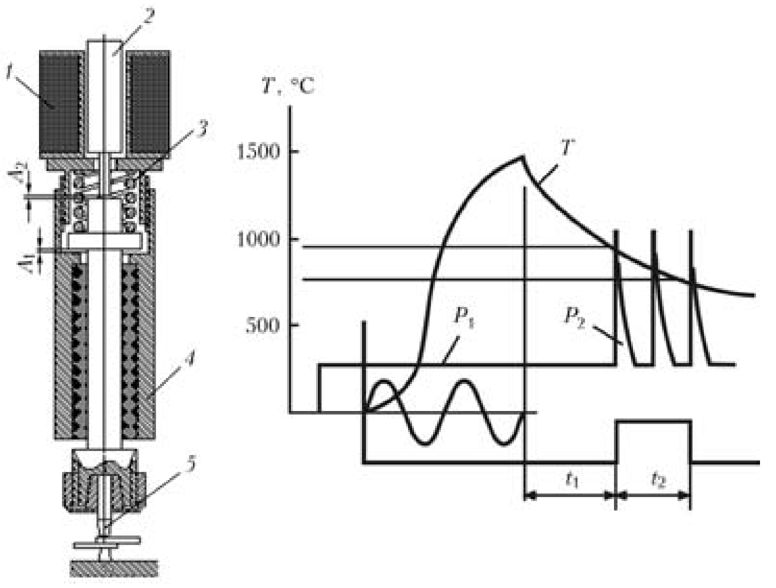

Figure 2. Schematic diagram of welding head with impact application of compression force and process cyclograms: *1*, *2* — respectively winding and core of solenoid; *3* — spring providing preliminary compression force; *4* — body; *5* — welding electrode

to the melting point of metal to be welded), as well as at its exceeding due to an abrupt increase of elastic properties of metal in the process of its cooling.

The results of carried out experiments on determination of temperature at which the application of pulses of impact compression forces leads to maximal increase of strength properties of welded joint indicate the range of 950–750 °C. However, coming from the technical difficulty of direct measurement of temperature of a weld spot metal during several fractions of a second, the indirect method of control by the time interval was used at the stage of development of this method, counted off after the moment of termination of heating, accepting the stability of parameters of heating and conditions of heat dissipation for initial conditions.

If necessary to perform seam welding of sheet materials the machine is equipped with mechanism of movement of parts being welded for the required distance between weld spots.

The obtained results of tests of welding head with electromagnetic system of application of impact compression force allow us to assume the possibility of transition from resistance spot welding to the variant of welding using indirect heating of parts being joined which represent interest from the point of view of welding of non-metallic materials. To realize the variant of indirect heating of parts being welded it is enough to complete the welding head with a plasmatron or gas-flame torch. Then the command device produces continuous succession of commands for impact treatment of a weld spot and instead of control of time range t_1 the distance between the source of indirect heating and welding head of impact thermomechanical treatment depending on the capacity of heating source and speed of movement of welding head is selected.

In this welding method the joining of sheet metal is performed in a form of succession of single weld spots with some overlapping, here each weld spot is subjected to impact effect of compression force to create mechanical compression stresses in it, sufficient for plastic deformation of weld metal.

CONCLUSIONS

1. The results of carried out tests of considered variant of welding head indicate the challenging application of electromagnetic system of impact influence of compression force in welding of steels of thickness of about 1 mm, for welding metals of larger thicknesses the transfer to the design of electrode unit using electrohydraulic effect is probably more necessary.

2. The presented design of welding head for treatment of a weld can be a base for development of new method of welding metals for which application of existing methods of joining are difficult or impossible.

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NEW INFORMATION ON «OLD» ELECTRODES

I.R. YAVDOSHCHIN and **O.I. FOLBORT**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The article gives information on upgrading of electrodes ANO-4 and ANO-21 to expand the range of electrodes and provide the maximum possible utilisation of raw materials from Ukrainian manufacturers. Also, it contains data on updating of regulatory documents for electrodes ANO-4 and UONI-13/45 to certify them to conformity with specifications RD 03-613–03 «Rules for Utilisation of Welding Consumables in Manufacture, Erection, Repair and Reconstruction of Technical Units for Hazardous Industrial Facilities».

Keywords: *welding electrodes, upgrading of electrodes, regulatory documents, construction and erection of industrial facilities*

The current market conditions are characterised by rapid changes in business environment and growth of competition. In this connection, it is necessary to promptly and adequately react to the associated risk. Following the concept of «continuous change to achieve stability», in the last years the E.O. Paton Electric Welding Institute has been active not only in developing new grades of electrodes, but also in improving developments of the last years to meet the constantly changing requirements imposed by their manufacturers and customers.

This study describes the point of upgrading of three grades of electrodes — ANO-21 and ANO-4 (the development of the E.O. Paton Electric Welding Institute), as well as UONI-13/55 (the development of the Central Research Institute for Materials (TsNIIM), Russia).

Versatile electrodes of the ANO-21 grade with rutile covering were developed for fillet, butt and overlap welding of 1–5 mm thick metal in all spatial positions, including for vertical downhill welding. The electrodes were produced with a 2–3.25 mm diameter rod. As proved by the experience of applying electrodes ANO-21 of the above diameters, they have high welding-operational properties: the arc is easy to ignite and remains stable in welding at both alternating and direct current of any polarity, the slag spontaneously detaches, the forming weld metal is fine-scaly, and the resulting weld is flat, dense and uniform. The use of these electrodes provides the required density of the welds even if the electrode covering is moistened, as well as in welding of metal having rust traces and various contaminations. The high arc stability at low amperage allows using household transformers with low open-circuit voltage. The above electrodes are easy to handle even for low-skilled welders.

Upgrading of electrodes of the ANO-21 grade was aimed at expanding their range and at the maximum possible utilisation of raw materials from Ukrainian manufacturers.

New modifications of the 2–5 mm diameter electrodes ANO-21 were designated as follows:

E46–ANO-21–∅2–3.25–UD / E432(3)–R11	GOST 9466–75 / TUU 05416923.001–95
E46–ANO-21–∅4–UD / E432(3)–R21	GOST 9466–75 / TUU 05416923.001–95
E46–ANO-21–∅5–UD / E432(3)–R31	GOST 9466–75 / TUU 05416923.001–95

It follows from the above designations that increase in diameter of electrodes ANO-21 leads to limitation of spatial positions, in which welding can be performed, other welding-operational indicators of the electrodes remaining practically unchanged.

The regulatory documents for electrodes ANO-21, including specifications and instructions, were updated allowing for the results of the investigations conducted. The statement of the sanitary and hygienic examination was issued, and the technology for production of the electrodes was mastered at Closed Joint Stock Company «Artyomovsk Machine-Building Factory «Vistek» by using the equipment available at the Factory electrode workshop.

Upgrading of electrodes ANO-4 and UONI-13/55 was caused by the need to meet requirements imposed by the National Agency for Control and Welding (NAKS) of the Russian Federation to the products supplied to this country by foreign manufacturers. Upgrading was preceded by efforts on adaptation of production of electrodes of the said grades to raw materials from the Ukrainian manufacturers, as well as on certification of manufacturers of electrodes ANO-4 and UONI-13/55 to conformity with specifications RD 03-613–03 «Rules for Utilisation of Welding Consumables in Manufacture, Erection, Repair and Reconstruction of Technical Units for Hazardous Industrial Facilities». Results of the above efforts are presented in the documents for the said grades of electrodes, including amendments in specifications of Ukraine for electrodes ANO-4 and UONI-13/55, which are supplied to the Russian Federation.

In particular, the section describing requirements to the electrodes indicates that they are used in manufacture, erection, repair and reconstruction of technical units applied at hazardous industrial facilities. The section dedicated to properties of the electrodes gives limitations (at a level of 0.75 of the requirements of GOST 9466–75) to values of the maximum permissible variations in thickness of the electrode covering and curvature. Also, it includes additional requirements for marking of each electrode and for deposition of an ionisation layer on an igniting tip of each electrode, as well as requirements to impact toughness of the deposited metal at a temperature of −40 °C.

The label attached to the packing, as well as the quality certificate should contain «NAKS Certificate # ______ of______ », along with the other data.

The above efforts were made on the initiative of CJSC «Artyomovsk Machine-Building Factory «Vistek».

BRANCH MEETING-CONFERENCE «STATUS AND MAIN DIRECTIONS OF DEVELOPMENT OF WELDING PRODUCTION IN OJSC «GAZPROM»

On November 15–19, 5th Branch Meeting-Conference «Status and Main Directions of Development of Welding Production in OJSC «Gazprom» was held at OJSC «Gazprom VNIIGAZ» in Moscow.

Scientists and leading specialists of research institutes and educational establishments of Russia, specialists on operation, diagnostics and repair of gas pipelines, as well as welding equipment manufacturers, including foreign manufacturers, participated in the Conference.

Altogether 88 presentations were made at the Conference: 16 presentations in the plenary meeting and 72 — in the two session meetings. A collection of presentation abstracts was published by the time the Conference was held.

P.G. Tsybulsky, Director General of «Gazprom VNIIGAZ» opened the Conference, and also made the welcome address. He wished successful work and business cooperation to the participants, briefly described the Conference goals and addressed the organizational matters.

Plenary presentations addressed strategic problems of development of gas transportation system (GTS) of «Gazprom», and session papers covered the following topics: session A — welding and related processes in operation and repair of gas production and transportation facilities; session B — welding and related processes in construction of gas production and transportation facilities.

Some of the priority directions of development of GTS of Russian «Gazprom» are guaranteeing safe transportation and storage of gas, integrity and specified level of technical condition of GTS facilities, economic and industrial safety in GTS operation. It is intended to achieve the defined objective by performing the following tasks:

- development of a system of controlling technical condition and integrity of GTS facilities based on risk analysis;
- conducting comprehensive technical diagnostics, analysis and forecasting of technical condition of GTS facilities, performed on the basis of the methods and technologies that are the most effective in technical and economic terms;
- analysis of natural, technogenous, management and financial risks of GTS operation;
- introduction of new (innovative) energy-saving technical solutions, materials, technologies and equipment.

Solution of the above tasks becomes particularly important for new main pipelines, passing through difficult-of-access regions or regions with extremal nature-climatic conditions (shelf areas of northern seas, high seismic activity) and requiring nonstandard design schematics of gas pipelines and manufacturing technologies, including special methods of cooling, thermal insulation and seismic protection.

It is noted that ensuring a high reliability of GTS is largely determined by the level of welding fabrication of «Gazprom». «Purpose-oriented integrated science and technology program of development of welding fabrication of OJSC «Gazprom» and Coordination

Council have an important role in its improvement. Coordination Council determines, in particular, development of new standards on welding fabrication.

A positive tendency has emerged in Russia over the recent years in development of new local technologies of welding in construction, in reconstruction and repair of the main gas pipelines. Here investigations to finish development of scientifically grounded design norms of evaluation of welded joint quality are important.

As regards new innovation projects, it is necessary to perform qualification testing of the technologies of automatic, mechanized and manual welding, as well as development of technical requirements to welded joints. Here it is noted that requirements should be defined not only proceeding from the condition of ensuring the specified level of performance, but also cost-effectiveness.

PWI specialists presented to the meeting participants a new approach to assessment of fitness-for-purpose of circumferential welded joints of pipelines made by automatic flash-butt welding. This approach focuses the specialists' attention on the need to develop requirements to mechanical properties of the joints allowing for the features of their welding, depending on the used welding procedure and quality of the produced joints.

Over the next years, it is planned to set up at «Gazprom VNIIGAZ» laboratory facilities on the basis of experimental production, for studying and mechanical testing of pipe samples and products, as well as for certification of welding production technologies. It is intended to fit these facilities with modern testing and welding equipment, nondestructive and destructive testing instruments for quality control of welded joint quality. For the first time «Gazprom» has implemented in practice the complete procedure of engineering evaluation of critical condition of circumferential welded joints of sea gas pipelines in construction, including certification of welding technology, and automated ultrasonic testing of circumferential butt joints. In addition to assessment of impact toughness of joint metal, fracture mechanics criteria were also determined, namely critical values of crack tip opening displacement (CTOD) and J-integral (J_{1c}). Requirements to admissible dimensions of defects were defined proceeding from performed studies of stress-strain state of circumferential butt joints in pipe laying and their fracture toughness (CTOD, J_{1c}) Such an approach complies with the modern level of guaranteeing

performance of welded joints made by arc welding processes, where the probability of formation of crack-like defects, including cracks, is quite high.

To guarantee the currently required qualification level of welding fabrication specialists, one of the largest technical centers on comprehensive training of welding-mounting teams was opened in the city of Gagarin (Smolensk region) on a territory equal to 6 hectares. The complex includes lecture-rooms, shops and sites fitted with the same equipment as in pipeline construction. A unique 200-meter training site was created which simulates the actual route conditions in construction of 1220 mm pipeline. The complete package of welding-mounting operations is performed in the training site.

Meeting-conference participants were able to see demonstrations of technologies of automatic, mechanized and manual welding for construction and repair of gas pipelines, as well as equipment and technologies for preparation, cutting, assembly, heating and heat treatment of welded joints. Other welding equipment of the following Russian and foreign companies was also demonstrated, such as CJSC «Pskovelektrosvar» (heavy electric welding equipment for welding pipes of different diameters); «Tekhnotron» plant (manufacturer of inverter-type welding equipment); CJSC «Uraltermosvar» (manufacturer of a wide range of welding equipment); «Lincoln Electric» (official distributor is «Weldsol»); and KEMPPI: the Joy of Welding.

Prof. V.I. Kyrian,
Corresp. Member of the NAS of Ukraine

REPORT-AND-ELECTION CONFERENCE OF THE UKRAINIAN WELDING SOCIETY

The regular Report-and-Election Conference of the Ukrainian Welding Society (UWS) attended by authorised representatives of all divisions of the Society was held in Kiev on the 25th of November 2010.

V.G. Fartushny, Candidate of Technical Sciences, President of UWS, reported about the work of the UWS Board during a period of 2006–2010. He gave a brief analysis of state-of-the-art of the welding industry in Ukraine and presented results of activities of the Board. Over 80,000 scientists, engineers and workers are involved in the welding industry of Ukraine. There are about 2,000 enterprises and companies fabricating welded structures, 39 manufacturers of welding equipment, and 64 manufacturers of welding consumables. 17 divisions (5 regional and 12 district divisions) were formed in structure of the Society. The Board of the Society consisted of 17 people. 9 persons formed Presidium of the Board. Vice-presidents of the Society were V.M. Ilyushenko, Candidate of Technical Sciences and Executive Director, and B.V. Yurlov, Candidate of Technical Sciences. UWS as an individual exhibitor participated in all national and a number of international welding exhibitions. The Society was a co-organiser of and active participant in a number of international and national conferences and workshops held in Ukraine and abroad. The Odessa Division of UWS annually hosted contests of professional welders of Ukraine. These contests became international in the last two years: welders from the Russian Federation and Belarus took part in them, along with the Ukrainian welders. Four books were published by recommendations of the UWS Board. Heading «Foreign Colleagues» was added to the «Svarshchik» (Welder) Journal. Information on the events arranged by the Society, on memorable dates and jubilees was published, and information exchange with some foreign welding journals was established. As to the cooperation, an agreement on cooperation with the Slovakian Welding Society was signed, and preliminary negotiations were held with welding societies of Rumania, Czech Republic and West Germany. The Board of the Society instituted an honorary award — N.N. Benardos Medal, which is conferred to scientists and specialists who made a great contribution to the progress of the welding industry in Ukraine, and to the development of UWS.

Report on the activities of the Auditing Committee was presented by V.V. Rogozhinsky, Committee Deputy Chairman.

Participating in debates and discussions on reports were V.I. Degtyar (Odessa), A.A. Kajdalov (Kiev), M.A. Laktionov (Sumy), N.G. Efimenko (Kharkov), P.P. Protsenko (Kiev), A.V. Krasko (Kiev), Yu.V. Butenko (Nikolaev), B.V. Yurlov (Kiev) and A.N. Vorobiov (Odessa). All the speakers approved of the work of the Board, and put forward many proposals on improvement of the activities of the Society for the next reporting period.

A new Board of UWS consisting of 21 people was elected: A.A. Abramov, Candidate of Technical Sciences, Chairman of the Khmelnitsk District Division of UWS; Yu.V. Butenko, Chief Welder of Gas Turbine Scientific and Industrial Complex «Zorya-Mashproekt»; N.V. Vysokolyan, Chairman of the Poltava District Division of UWS; V.I. Degtyar, Candidate of Technical Sciences, Director of Research and Production Centre «Welding»; N.I. Duda, Director General of Open Joint Stock Company «Zhitomir Factory for Metal Structures»; N.G. Efimenko, Doctor of Technical Sciences, Chairman of the Kharkov District Division of UWS; V.M. Ilyushenko, Candidate of Technical Sciences; A.A. Kajdalov, Doctor of Technical Sciences; A.I. Komissar, Director General of Limited Liability Company «Fronius-Ukraine»; N.M. Kononov, Chairman of the Dnepropetrovsk District Division of UWS; A.M. Kostin, Candidate of Technical Sciences, Chairman of the Nikolaev District Division of UWS; V.T. Kotik, Candidate of Technical Sciences, Director of the Ukrainian Welding Qualification Committee; A.V. Krasko, Chairman of the Central Regional Division of USW; M.A. Laktionov, Candidate of Technical Sciences, Chairman of the Sumy District Division of UWS; Ya.I. Mikitin, Chairman of the Kherson District Division of UWS; G.V. Pavlenko, Chairman of the Crimean Regional Division of UWS; V.N. Palash, Candidate of Technical Sciences, Chairman of the Western Regional Division of UWS; P.P. Protsenko, Candidate of Technical Sciences, Director of the Inter-Industry Training Certification Centre of the E.O. Paton Electric Welding Institute; V.G. Fartushny, Candidate of Technical Sciences; K.P. Shapovalov, Chairman of the Donetsk District Division of UWS; and B.V. Yurlov, Candidate of Technical Sciences.

A.N. Vorobiov, S.V. Oleksienko and V.V. Rogozhinsky were elected to the Auditing Committee.

V.G. Fartushny was elected the President of UWS. A.A. Kajdalov, Doctor of Technical Sciences, and B.V. Yurlov, Candidate of Technical Sciences, were elected vice-presidents, and V.M. Ilyushenko, Candidate of Technical Sciences, became the Executive Director of UWS.

Cand. of TechSci V.M. Ilyushenko, PWI

5th INTERNATIONAL SEMINAR «NEW RESEARCH AREAS IN THE FIELD OF WELDING LIVE SOFT TISSUES»

On November 26–27, 2010 the 5th International Seminar «New Research Areas in the Field of Welding Live Tissues» was held in Kiev at the E.O. Paton Electric Welding Institute. More than 130 persons (surgeons, representatives of regional offices of the MOH of Ukraine, distributor companies, scientists and specialists in the field of biological and medical sciences, developers of medical equipment) from 16 regions of Ukraine, Russian Federation, Belarus Republic, Bulgaria, Poland, Macedonia, and the USA participated in the seminar. Seminar organizers were PWI and International Association «Welding».

The first day of the seminar was devoted to consideration of the results of recent studies on electric welding application in medicine by a number of the seminar participants. On the second day all the interested persons were able to try the technology and PWI new developments directly during an animal test. Foreign and Ukrainian surgeons participating in the practical part of the seminar, noted the importance of acquiring the skills directly from the developers, and were able to more profoundly appreciate the features of application of live tissue welding and its main advantages over coagulation. 30 papers were presented in the seminar dealing with theoretical and experimental aspects of the process of high-frequency (HF) electric welding of live tissues, development of equipment and tools, as well as experience of clinical application of this new surgical technology.

Opening the seminar, Prof. B.E. Paton noted that the value of these seminars lies in the possibility of exchange of experience on application of this most advanced technology in different directions of modern surgery. Joint discussion and experimental studies allow «...finding bottlenecks in the studied area and making appropriate corrections». Our goal is not to stop on the achieved level, but move ahead, improving the quality and widening the sphere of application of tissue-saving HF-electric welding technology. Prof. B.E. Paton further noted that over the ten year period of development of this advanced technology there are still a lot of unsolved problems of manufacturing and reconditioning of the respective electrosurgical tools that considerably limits its propagation.

A number of presentations were made at the seminar. In the presentation by G.S. Marinsky, Dr. of Sci (Eng.) (PWI), it was noted that by now PWI together with International Association «Welding» developed a new generation power source for HF-electric welding of soft tissues under an innovation project. The new modification was developed taking into account the experience of operation of earlier applied equipment, as weld as recommendations and proposals of surgeons of various specialities. This source which was tentatively designated EKZ-300-5, is at the stage of laboratory testing and is being prepared for batch production. At the same time, PWI is working on setting-up large-scale production of new tools for HF-electric welding of soft live tissues. Presentation by O.N. Ivanova and D.D. Kunkin (International Association «Welding») was devoted to improvement of instrumentation system for recording electrical parameters in live tissue welding. This system was the basis for development of a diagnostic complex for assessment of the quality of produced welded joint directly during the surgery in real-time mode. In the paper by M.P. Zakharash, Corresp. Member of AMSU (O.O. Bogomolets National Medical University, Kiev), devoted to bioethical aspects of electric welding of live organs and tissues in surgery, in particular, it was noted that an important bioethical aspect and priority of the technology of HF-electric welding of organs and tissues is the possibility of its application for rendering emergency surgical assistance in maximum short time to a large number of casualties in military conflict zone, in terrorist attacks, natural disasters, mine accidents, transportation and other emergencies. Presentations by Prof. A.V. Makarov and Cand. of Sci A.V. Linchevsky (Kiev City Clinical Hospital # 17) were devoted to the peculiarities of application of this technology for welding parenchymal organs at their rupture. It was noted that the main disadvantage of the equipment is a complete or partial absence of a tool for laparoscopic operations that does not permit performance of minimally invasive surgeries. In addition, in his paper Prof. A.V. Makarov substantiates the need to ensure favourable conditions for applying energy impact to the tissue that were documented using

the PWI developed diagnostic complex for assessment of the quality of the produced welded joint. Re-production of these conditions of energy impact further on allows a considerable lowering of the probability of tissue overcoagulation. In the paper by V.R. Zaremba (Head of Surgical Department of District Pediatric Hospital, Zhitomir) it is stated that despite the obvious advantages of welding, the capabilities of this technology cannot be fully used, in particular, because of unsatisfactory level of tool manufacturing quality and, hence, its short operating life (156.2 operations on average, and not more than 20 operations in the case with the laparoscopic tool). In addition, absence of fixation of the pressure of tool working parts aggravates the influence of the human factor and leads to unstable result of tissue joining, particularly in the manual mode. The paper by V.K. Tsap, representative of the company-distributor of live tissue welding equipment EK-300M1, highlighted the problems of technology promotion in the Ukrainian market. He noted, in particular, that the market capacity is equal to more than 8000 in-patient hospitals, and the number of applied systems in them is not more than 100 pcs. The causes for such limited application of local equipment are: insufficient budget funding of the facilities by MOH of Ukraine and inefficient approach to utilization of the allocated funds; absence of special state programs on introduction of this technology; insufficient data base and surgeons' conservatism.

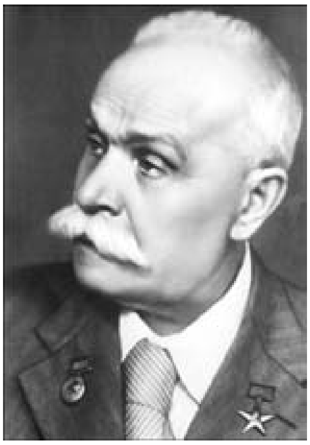
In conclusion, Prof. B.E. Paton noted that «... since the time, when 10 years ago this technology was first applied under clinical conditions on humans, about 130 surgical procedures were developed that have been accepted in more than 50 clinics of Ukraine. So far, more than 65,000 operations have been performed, all of them successful. However, it is necessary to carry on research with the purpose of further improvement and development of new samples of equipment and tools for implementation of this advanced technology, development of new procedures, as well as searching for methods of precision energy impact on live structures.

In our opinion, each surgeon should master the new tissue-saving technology. For this purpose it is necessary to develop a national program on improvement of rendering emergency surgical assistance with application of the electrosurgical technology.

«Electric welding» term is gaining popularity in the world of medical equipment manufacturers both in the West and here in Ukraine. We appreciate such recognition. However, use of this term does not always guarantee the high quality of the welded joint. We, as the originators of this process, know what is required to guarantee the quality and how critical it is, when human life is at stake».

Cand. of Sci (Eng.) O.N. Ivanova,
Eng. D.D. Kunkin, IA «Welding»

THE 3d PATON READINGS-2010

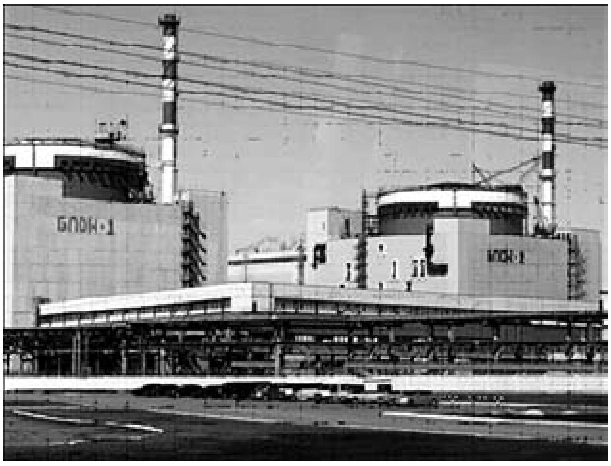


The 3d Paton Readings-2010 took place in Volgodonsk in the Information Center of Volgodonsk NPP on November 27, 2010. It was a meeting of young generation, students, future welders, metallurgist-technologists with scientists and specialists, workers and pedagogues, inventors and public figures. This event was marked by Paton phenomenon which includes a number of interdisciplinary trends of science and production and has appeared during almost secular way of development of metallurgy and welding. The Paton welding and metallurgical technologies were made the main innovation factors of progress by thousands of scientists and specialists for many enterprises of metallurgy, power engineering, nuclear engineering, aircraft construction, aerospace branch, shipbuilding, oil and gas branches, agricultural engineering, transport engineering that allowed reaching the new level of materials science and construction, obtaining of the materials and new quality of welding and metallurgical processes.

Many scientists and specialists from the higher institutes of education, including Omsk State Technical University, Lipetsk State Technical University as well as secondary vocational training, including Volgodonsk Polytechnic School — branch of the National Research Nuclear University MIFI: RI and DB, including VNIIAEP, DB of special metallurgy of FSUF «Torij», P.A. Yudin Metallurgical Center, CJSC NTTs and SPC SKIBR (Moscow–Dubna), enterprises of nuclear power engineering complex, including ATOMMAShEKSPORT with educational Center for training and certification of welders, V. Tudvasev School (PE TsPiAS OJSC «Atommasheksport», Belgorod Plant of Power Machine Building (BZEM «Energomash»), «Energomash-Atommash» plant with Engineering Center of «Energomashcorporatsii», Lipetsk BCD CJSC «Kislorodmontazh», Welding-erection company MONREM, Service of chief engineer of Volgodonsk/Rostov NPP on repair and service reliability, Volgodonsk Plant of Metallurgical and Power Equipment, enterprises of business and management, welders with 40–50 years' experience, specialists of welding centers, students and trainees, activists of the Russian Nuclear Society responded to participation in the Paton Readings.

Specialists of welding production, lecturers and students, leaders of creative collectives and productions, public activists gave the reposts and information during the readings.

Welding standards, including SNiPs, staff, research and technological innovations in relation to a strategy of nuclear generation and construction of reactors for NPP in a period up to 2020, the problems of international cooperation, raw material trend of economy, stopping development of welding, power engineering, metallurgical and building capacities, the problems of management modernization and innovation economy were primarily discussed. The reports on the following themes were made: «The Paton world historical experience of establishment of welding metallurgical productions and interdisciplinary cooperation between the scientists and specialists», «Training of welding staff for nuclear industry in the ranges of nuclear strategy of Russia up to 2020–2030», «Organizing of works on repair welding technologies and reengineering on service reliability of NPP equip-



ment», «Why I've chosen a welding occupation», «Equipment for electroslag welding of case-shaped parts and pieces of equipment for nuclear power designation», «Application of Russian repair tribotechnologies for modernization of the aircraft engines of helicopters and planes of transport aviation of Russia and tool manufactures of Ukraine, Belarus and Kazakhstan», «Coordination of technical works and preparation of welding production during filling of important orders for foreign companies and manufacture of pipeline elements for HPS, NPP and oil-and-gas complex», «Innovation equipment for reducing of heat emission in arc welding process», «Design support of welding-erection works on the energy blocks of Rostov NPP under construction», «Scientific and technological complex for production of modern materials and technologies of special electrometallurgy» and many others.

Interesting discussion and exchange of experience arose in the course of reports in such issues as practical welding without «commercial secrets», complexities of flaw detection, examination and certification of the latest technologies in the field of special electrometallurgy and fast education of details of welding work, problems with re-teaching of students.

The papers indicated that the development of welding science is characterized by wide application of the achievements of related branches of knowledge: solid-state physics and chemistry, electrical engineering and electronics, materials science and metallurgy, mechanics and mathematics. There is a necessity under market conditions that many welding and thermal sets to be designed and constructed mobile for application under field conditions and in transportable variant in equipping by the mobile laboratories, capable by a radial method to service the consumers that do not have the possibility to reequip for manufacture of single products, but capable to find the means for carrying out one-time work (services) using high-efficiency devices on wheels or flights.

Welder-scientists, based on the achievements of natural and technical sciences, successfully solve the tasks, related with advancement of technology for welding metallic and non-metallic materials, development of welded joints, assemblies and structures operating safely under the most complex and various conditions of modern production.

Technical condition of Russian welding production is determined by advanced welding sub-sector. It includes number of leading centers of welding science and engineering: Russian Institute of Welding (VNIIESO), P.A. Yudin Metallurgical center, VNII ETO, TsNIITMASh, St.-Petersburg Electrotechnical University, the Alliance of Welders of St.-Petersburg and North-West region, V.P. Vologdin VNII TVCh, TsNII CM «Prometey», Plasma-Center, Laser Association for CIS, «Tena» Technological Center, Pskov Factory of Welding Equipment, FSUE «Torij», Novozybkov «Induktor», Novocherkassk Plant of Welding Electrodes, National Attestation Committee on Welding and many others. Metallurgical branches, surviving capacities of special electrometallurgy and new productions of laser-plasma technologies of metal treatment have a great potential.

All the participants of the readings are convinced in the necessity of renewal of tutorship during education of top-level welders since the graduates often do not have enough theoretical knowledge for fulfillment of critical works. It is necessary to overcome «dependence» on raw materials and financial errors for carrying out staff, educational and technological modernization.

Modernization of management in all spheres, including science, education, industry and economy takes place in Russia despite the economy crisis grips. Present Paton Readings took place on the eve of reaching the design power on the 2nd reactor of Volgodonsk NPP. Number of welders today have good professional opportunities and will have in the following years during development of equipment and construction of the 3rd and 4th reactors of VNPP.

N.I. Bakumtsev, Organizer of the Readings and scientific coordinator of the Program