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MATHEMATICAL MODELLING OF REACTIVE DIFFUSION PROCESSES IN BRAZE-WELDING OF OVERLAP JOINTS OF THE TITANIUM--ALUMINIUM TYPE

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Mathematical model of the processes of reactive diffusion in overlap welded joints of the titanium--aluminium type was developed. Degree of the risk of formation of a brittle layer of intermetallic $TiAl_3$ depending upon the welding process parameters was assessed. The data were generated on distribution of elements within the welded contact zone.

K e y w o r d s : braze-welding, titanium, aluminium, dissimilar joint, reactive diffusion, layer of intermetallic compound, modelling

One of the characteristic features of welding of dissimilar metals is the risk of formation of intermetallic compounds within the welded contact zone. The presence of a considerable amount of such inclusions may lead to a substantial decrease in operational properties of a welded joint [1–3].

In this connection, to optimise parameters of a corresponding production cycle it is necessary to take into account kinetics of the processes of reactive diffusion occurring in welding of dissimilar joints.

Experimental investigations of heat and mass transfer during welding involve substantial difficulties and costs. Therefore, of certain interest in this respect are the methods of mathematical modelling of the corresponding processes, based on the advanced numerical methods [4].

The mathematical model was developed for this purpose, describing the processes of reactive diffusion at the boundary of a welded joint by an example of production of an overlap joint between titanium and aluminium by the braze-welding method.

Characteristic features of the processes of reactive diffusion in braze-welding of overlap joints of the titanium–aluminium type. Welding of titanium to aluminium involves the problem of deterioration of quality of the resulting dissimilar joint, which is caused by formation of intermetallic layers within the welded contact zone [1, 5]. As seen from the constitutional diagram of the titanium--aluminium binary system (Figure 1), these metals are characterised by low mutual solubility. Therefore, when their liquid phases are mixed together, it is impossible to avoid formation of brittle intermetallic compounds.

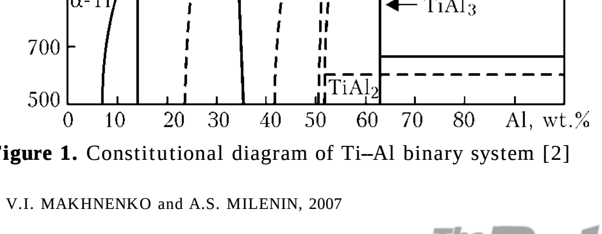

Figure 1. Constitutional diagram of Ti–Al binary system [2]

Because of a substantial difference in melting temperatures of titanium (1668 °C [6]) and aluminium (660 °C [7]), the braze-welding method can be employed to join these metals. The point of this process is that metal with a higher melting temperature (titanium) remains solid under the effect of a welding heat source, and metal with a lower melting temperature (aluminium) melts to form a braze-welded contact [1, 2, 5, 8]. This allows the temperature of heating the contact surfaces of the liquid and solid metals to be minimised and, therefore, the risk of formation of intermetallic layers to be decreased.

The process of formation of an intermetallic layer near the braze-welded contact surface can be conditionally subdivided into the following stages [9]:

- relaxation of a peak of the inter-phase energy at the liquid--solid metal interface;
- formation of islands of a new phase in locations of microdefects on the solid metal surface, growth of these islands over the contact surface, and their coalescence into a continuous interlayer;
- diffusive growth of the intermetallic layer in a direction from the surface of the dissimilar contact.

Also, it should be noted that during the first two stages of formation of the intermetallic layer its thickness is small. Therefore, it does not cause a considerable decrease in operational properties of the resulting welded joint [8, 10]. The total time of these two stages determines the so-called latent period of formation of intermetallics. The presence of this period allows formation of brittle intermetllic layers with a thickness sufficient for substantial deterioration of operational properties of a weldment to be avoided in the welded joints between titanium and aluminium.

Despite the fact that the constitutional diagram of the Ti--Al binary system shows the presence of four stable intermetallic compounds (Ti_3Al, TiAl, $TiAl_2$, $TiAl_3$), only stoichiometric compound $TiAl_3$ may be formed in braze-welding of titanium to aluminium, whereas the amount of other intermetallic phases is either negligibly small, or they are absent at all [11]. This is attributable to different ratios of the rate of reaction of formation of corresponding intermetallic compounds to the rate of arrival of elements to the reaction (diffusion) zone in welding, which cannot be covered by the constitutional diagram of the binary system.

The developed mathematical model considers the process of reactive diffusion with formation of a layer of intermetallic compound $TiAl_3$.

Modelling of the heat transfer and reactive diffusion processes in braze-welding of overlap joints of the titanium–aluminium type. One of the examples of braze-welding of a dissimilar joint of the Ti–Al system is argon-arc overlap welding of titanium to aluminium plates using an aluminium filler wire [1, 5]. The flow diagram of this process is shown in Figure 2. The concentrated heat source (in this case it is the welding arc, although lasers are employed now in such flow diagrams [2, 8]) is moved along the welded contact to melt the aluminium wire and incipiently melt the aluminium edge. Liquid aluminium spreads over solid titanium (the titanium edge can be preliminarily aluminised) to form the braze-welded contact. To prevent overheating of the weld pool and maintain the solid state of titanium, the welding heat source is moved quickly enough, which makes it reasonable to use corresponding 2-D models for mathematical modelling of the heat and mass transfer processes.

Geometric parameters of the resulting welded joint are as follows:

Width of titanium plate, mm	70
Width of aluminium plate, mm	70
Thickness of titanium plate, mm	2
Thickness of aluminium plate, mm	8
Height of the weld bead, mm	6.2
Weld width, mm	20.3
Length of contact line between titanium and aluminium parts of the welded joint, mm	30

Main characteristics of the welding process are as follows:

Speed of movement of heat source along the joint, mm / s	4
Power of heat source, kW	4.4
Heating efficiency, %	50
Diameter of the weld spot, mm	3

Geometric dimensions of the weld bead are taken up with allowance for full strength of the welded joint.

It should also be noted that this mathematical model does not allow for metal spreading as long as the bead of a final shape is formed, because the effect of this process on the character of heat transfer is low and shows up only in a small region located ahead of the welding heat source.

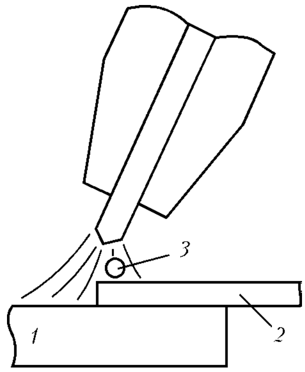

Figure 2. Flow diagram of the process of production of overlap braze-welded joint of the Ti–Al system [5]: *1, 2* — aluminium and titanium parts of workpiece; *3* — aluminium filler wire

Kinetics of the 2-D temperature field can be described using a numerical solution of the thermal conductivity equation:

$$C(x,\ y,\ T)\,\frac{\partial T(x,\ y,\ t)}{\partial x} = \frac{\partial}{\partial x}\left(\lambda(x,\ y,\ T)\,\frac{\partial T(x,\ y,\ t)}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda(x,\ y,\ T)\,\frac{\partial T(x,\ y,\ t)}{\partial y}\right), \quad (1)$$

where $T(x, y, t)$ is the temperature at point (x, y) of the rectangular system of coordinates at time moment t, °C; $\lambda(x, y, T)$ is the thermal conductivity of metal at point (x, y) with temperature T, J / (mm·s·°C); and $C(x, y, T)$ is the volumetric heat capacity of material, J / (mm^3·°C).

For correct statement of the problem of thermal conductivity it is necessary to allow for initial and boundary conditions. The following conditions are assumed as such:

$$-\lambda(x,\ y,\ T)\,\frac{\partial T(x,\ y,\ t)}{\partial n}\Big|_{(x,\ y)\,\in\, G} = \alpha_t(T(x,\ y,\ t) - T_a); \quad (2)$$

$$T(x,\ y,\ 0) = \begin{cases} T_L^{Al}, \text{ if } (x,\ y) \in F, \\ T_a, \text{ if } (x,\ y) \notin F, \end{cases} \quad (3)$$

where n is the normal to the surface; G is the boundary of the contact of metal in the welded joint with a surrounding atmosphere; α_t is the thermal conductivity coefficient equal, according to the experimental data, to 0.0002 W / (mm^2·°C) in the case of contact with the surrounding atmosphere; T_L^{Al} = 600 °C is the temperature of aluminium melting, °C; T_s is the temperature of the surrounding atmosphere, °C; and F is the region of the weld delineated by curve $AOCB$ (Figure 3).

Numerical solution of thermal conductivity equation (1) with boundary (2) and initial (3) conditions for welding a dissimilar joint with the above geometric parameters allowed revealing the character of time variations of the temperature field. Calculations were made for the entire cross section area of a welded structure.

Therefore, the time dependence of temperature of the titanium to aluminium contact surface being

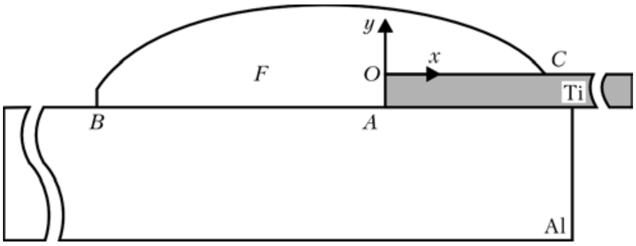

Figure 3. Schematic of overlap welded joint of the titanium--aluminium type [1, 5]

known, it is possible to estimate the risk of formation of an intermetallic layer. Dependence of the latent period of formation of intermetalic compound $TiAl_3$ upon the temperature at the boundary of the titanium to aluminium surface contact is shown in Figure 4. The following form of coefficient χ of the risk of formation of intermetallics was considered to allow for the latent period in the case of the time-varying temperature field [5]:

$$\chi = \int_0^{t_0} \frac{dt'}{\tau(T)}, \tag{4}$$

where t_0 is the foreseeable time of dwelling of the specific point of contact of titanium with liquid aluminium at high temperature; $T = T(t')$ is the temperature at the above contact point at time moment t', $0 \le t' \le t_0$; and $\tau(T)$ is the time of the latent period, which is taken up from Figure 4. In this case, meeting the $\chi < 1$ condition guarantees the absence of intermetallic layers of a considerable thickness.

To illustrate calculations of this criterion in the case of the overlap welded joint between titanium and aluminium, Figure 5 shows distribution of the coefficient of the risk of formation of intermetallic $TiAl_3$ along the OC line of the surface contact of metals (see Figure 3) at different spatial positions of the welding heat source relative to the end of the titanium part of the welded joint (values of $\chi > 1$ are not shown in the plots). As seen from the Figure, the coefficient

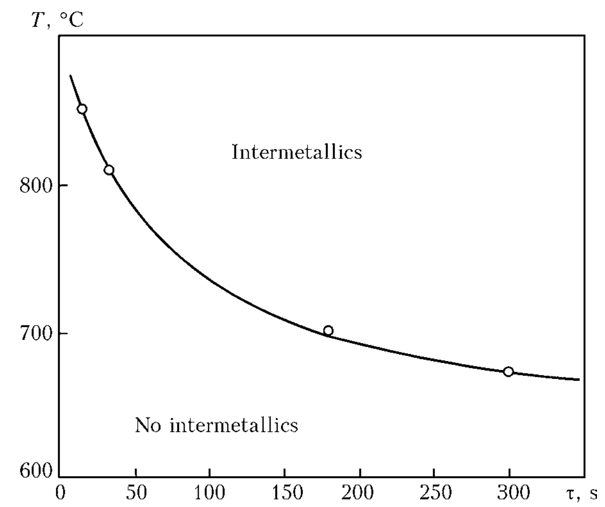

Figure 4. Temperature dependence of time τ of the latent period of formation of intermetallic compound $TiAl_3$ at the boundary of surface contact of solid titanium with liquid aluminium [5]

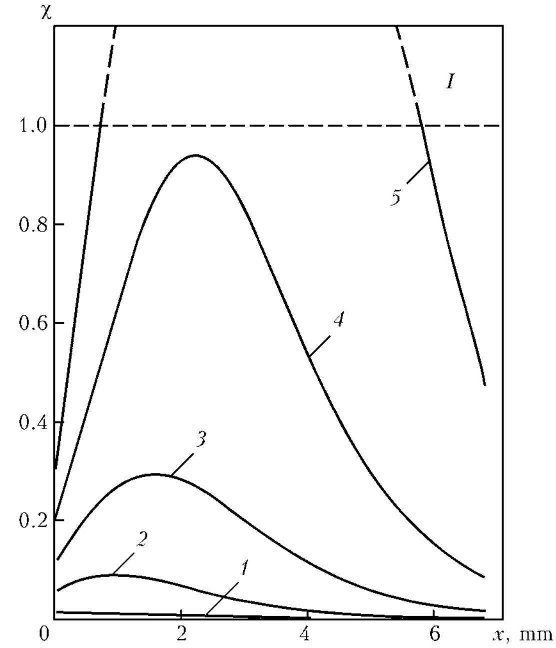

Figure 5. Dependence of coefficient χ of the risk of formation of $TiAl_3$ at different points of the surface of welded contact in a dissimilar joint upon the heat source position: *1* — x_0 = --2.7; *2* — 0; *3* — 1; *4* — 2; *5* — 3 mm; *I* — region of high risk of decrease in service properties of a structure because of the presence of intermetallic layers

of the risk of formation of intermetallics greatly depends upon the position of the welding heat source. In this case, if the source is located either near the end of the titanium part of the welded joint, or is shifted towards the aluminium part, this practically guarantees the absence of an intermetallic layer. However, if the source is shifted towards the titanium part of a workpiece to a distance of 2 mm or more, then the formation of the brittle intermetallic layers can hardly be avoided. These results are in good agreement with the process parameters of braze-welding of overlap joints between titanium and aluminium, developed on the basis of experimental data [5].

In some cases the presence of the continuous intermetallic layer of a certain thickness does not decrease the total strength value of a weldment (whereas, e.g. the welding process causes a substantial decrease in strength of the heat-affected zone on the aluminium part of a workpiece). In this connection, of certain interest is to evaluate thickness of the intermetallic layer in the case where the $\chi < 1$ condition is not met.

As noted above, if the time of dwelling of the titanium to aluminium surface contact zone at high temperatures exceeds the time of the latent period, this involves formation of the layer of intermetallic $TiAl_3$, the growth of which is determined by the rate of mutual diffusion of atoms of the elements being welded.

The mass transfer process was described within the frames of the 2-D Fick law [12], which has the following form in the case of a probable chemical reaction of the diffusive material components:

Table 1. Values of coefficient of diffusion of titanium, D_{Ti}, into aluminium [13]

Content of [Ti], wt.%	$D_{Ti}\cdot 10^9$, mm^2 / s, at T, °C					
	100	200	300	400	500	600
5	0.573	1.320	3.062	7.138	16.699	39.179
25	0.703	1.487	3.206	7.034	15.665	35.332
50	0.866	1.696	3.387	6.905	14.372	30.523
75	1.033	1.904	3.567	6.775	13.079	25.713
95	1.159	2.071	3.711	6.672	12.045	21.866

Table 2. Thermal-physical properties of titanium and aluminium used in the mathematical model [13, 14]

Thermal-physical parameters	Ti	Al
Thermal conductivity (at T = 20–700 °C), J / (°C·cm·s)	0.118–0.114	2.254–2.500
Heat capacity (at T = 20–700 °C), J / (g·°C)	0.54–0.69	0.90–1.22

$$\frac{\partial c_i}{\partial t} = \frac{\partial}{\partial x}\left(D_i(x, y, T, c_i)\,\frac{\partial c_i}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_i(x, y, T, c_i)\,\frac{\partial c_i}{\partial y}\right) - V_i(c_i, c_{TiAl_3}), \quad (5)$$

where c_i is the concentration of the i-th element (i = Al, Ti) at time moment t; D_i is the coefficient of diffusion of the i-th element, mm^2 / s; T is the temperature at point of the welded joint under consideration, having the (x, y) Cartesian coordinates, °C; and $V_i(c_i, c_{TiAl_3})$ is the function of a volumetric source of the i-th material, l / s (if the proportion of aluminium and titanium in a solution is such that there is an excessive amount of one of these elements over the limit of their mutual solubility, this leads to decrease in the concentration of the excessive element to form a corresponding amount of intermetallic).

Initial concentrations of elements in titanium and aluminium parts of a workpiece serve as initial conditions for this problem.

The following condition is used as the boundary one for equation (5):

$$c_i \Big|_{\infty} = c_i^0, \quad (6)$$

where c_i^0 is the initial concentration of the i-th element; and $c_i|_\infty$ is the same, but at a substantial distance from the contact region. For the case under consideration, allowing for a short time of contact of metals welded at high temperatures, it can be assumed that no changes in composition of the metals due to mutual diffusion occur in the regions located at a distance of 1 mm from the plane of the welded contact. Accordingly, the calculations were made within the above limits from equation (5) along the line of the dissimilar contact.

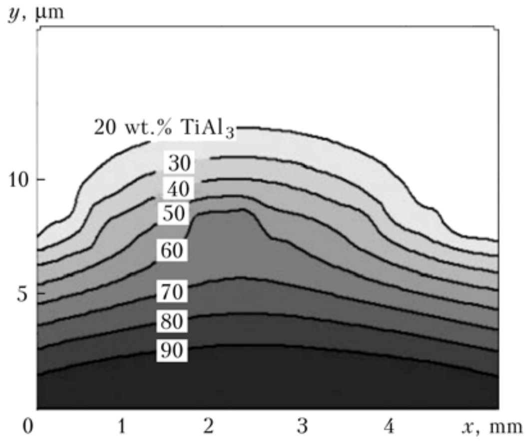

Figure 6. Distribution of intermetallic $TiAl_3$ through width and depth of the welded contact

Diffusion coefficient D_i is known to depend upon the temperature and composition of metal within the zone under consideration. Its values are given in Table 1. Thermal-physical properties of titanium and aluminium, which are used in the given model, are presented in Table 2 [13, 14].

As described above, the intermetallic layer about 5 mm wide (see Figure 5) is formed near the contact surface with the welding head source located at a distance of 3 mm towards the titanium part of the joint. Solutions of the heat transfer and reactive diffusion problems for this case made it possible to determine the distribution of titanium, aluminium and intermetallic $TiAl_3$ in a region of the titanium to aluminium surface welded contact.

Figure 6 illustrates the distribution of intermetallic $TiAl_3$ in a region of the welded contact with the welding heat source located at 3 mm towards the titanium part of the joint. As seen from the Figure, the distribution of the intermetallic compound along the surface of the contact is non-uniform: kinetics of the reactive diffusion processes is more intensive within the zone of location of the centre of the heat source spot, which shows up in a substantial increase in the content of intermetallic $TiAl_3$, whereas it decreases closer to the periphery. The intermetallic layer grows towards the aluminium part of a workpiece, which is attributable to a lower solubility of titanium in aluminium than aluminium in titanium, as well as to a stoichiometric proportion of titanium and aluminium in $TiAl_3$.

CONCLUSIONS

1. The effect of the process parameters on the risk of formation of a brittle layer of intermetallic $TiAl_3$ at the boundary of the welded contact was analysed within the frames of the developed mathematical model of thermal-diffusion processes occurring in braze-welding of the titanium–aluminium type joints.

In particular, it was proved that the optimal position of the weld spot centre is at a level of the end of the titanium plate, or with a shift towards the aluminium plate, which was confirmed by experimental data.

2. The 3 mm shift of the source towards the titanium plane was found to cause formation of a brittle intermetallic layer about 5 mm wide and up to 15 μm thick.

3. Growth of the intermetallic layer occurs towards the aluminium part of a weldment, and is determined by the rate of diffusion of titanium and by its insignificant solubility in aluminium.

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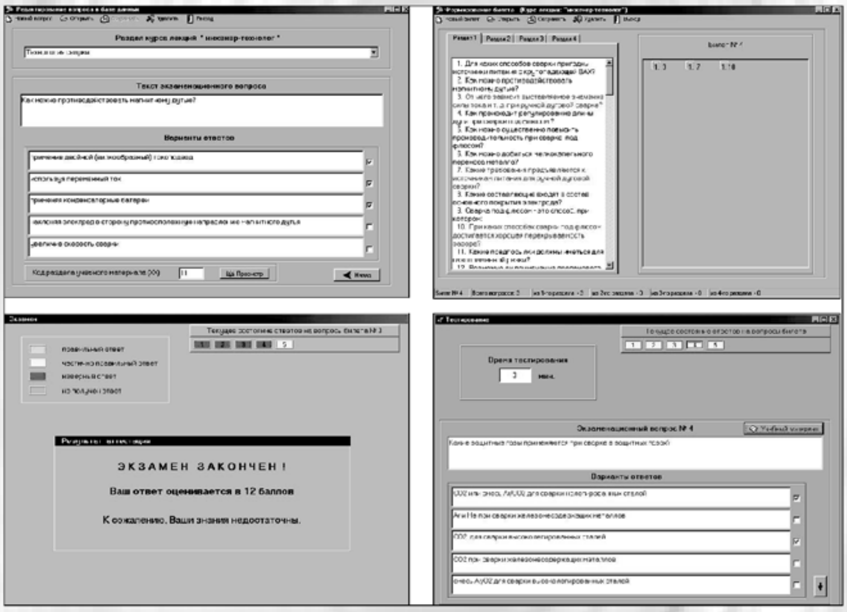
COMPUTER SYSTEM FOR EXAMINATION WITH TRAINING ELEMENTS

Purpose. The computer system is intended for certification of specialists. It includes three independently operating modules: database editor, examination subsystem and testing subsystem. The database editor is used by a trainer to prepare examination questions (EQ) and formation of question cards (QC). The examination subsystem tests knowledge of a trainee on the basis of a question card selected by using a sensor of random numbers from the formed set of the cards, and draws up the examination protocol. The testing subsystem serves for current self-testing of the trainee's knowledge of a separate section of the training course. It performs all functions of the examination subsystem and, additionally, allows (after giving the full answer to a card) giving other variants of the answers if a trainee has made a mistake. To find a correct answer to the QC question, the possibility exists of having an information support, which is provided for by using an electronic manual. The Figure shows the format of QC EQ from the EQ database and results of the official testing and certification with the possibility of having the information support.



Application. The system can be used to test and certify specialists at industrial enterprises, educational institutions, qualification improvement courses, etc.

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FEATURES OF FORMATION OF PLASTIC DEFORMATIONS AT ELECTRODYNAMIC TREATMENT OF WELDED JOINTS OF St3 STEEL

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The effect of treatment of specimens of St3 steel base metal and welded joints with pulses of electric current on peculiarities of formation of macroplastic deformations in the joints subjected to uniaxial tension has been studied. An experimental procedure has been developed, which is used to investigate the mechanism of formation of L uders lines in uniaxial tension under the electrodynamic impact conditions. It is established that the characteristic simultaneous formation of plastic deformations induced by welding and current impact takes place in electrodynamic treatment of welded joints on steel St3.

Keywords: electrodynamic treatment, plastic deformations, low-carbon steel, Luders lines, uniaxial tension, residual welding stresses, butt joint, flat blade-shaped specimen

Advance of modern engineering necessitates a search for promising approaches to extension of the residual life of metal structures. One of the new directions in this area is development of the methods for treatment of structural materials and their welded joints based on the impact of the electromagnetic field on current-conducting materials [1], which, specifically, is electrodynamic treatment (EDT). By converting the electric energy of current pulses into the energy of the electromagnetic field initiating the deformational processes in the metal, it is possible to influence the mechanical properties of structural materials. Interaction of electrodynamic processes with external loads applied to welded joints of the treated item may lead to development of plastic deformations in the welds and HAZ, influencing the mechanical properties of structural materials.

One of the factors lowering the metal structure performance, is presence of residual welding stresses (RS), which adversely affect the strength and fatigue resistance of welded joints. EDT of materials [2] and their welded joints [3] allows initiating the processes, which may lower the overall level of the stressed state of metal structures.

Investigation results given in [3] indicated that at the impact of current pulses local deformations develop in the metals and their welded joints, the magnitudes of which reach the material yield point σ_y. The derived data were based on measurements of relative deformations at different parameters of the electric-pulse impact and external loading. Experimental procedures implemented in [3, 4] do not allow a visual examination of nature of running of the plastic deformation processes at electrodynamic impact. An effective method of visual assessment of the distribution of plastic deformation fields in low-carbon steels is based on investigations of distribution patterns of Luders' lines (LL), the formation of which is due to development of local yield, i.e. LL develop when the metal has a pronounced yield limit, which is characteristic for low-carbon steels. Stress concentration promotes LL appearance and development [5]. Study of their formation at EDT of low-carbon steels allows revealing the regularities of running of plastic deformation of the material at the impact of current pulses.

The purpose of this work is studying the regularities of formation of plastic deformation fields in welded joints of low-carbon steels at EDT based on studying the LL distribution patterns.

In order to assess EDT influence on LL distribution blade-type specimens from low-carbon steel St3 4 mm thick with the gauge size of 110×30 mm were used. The specimens were first subjected to mechanical polishing. EDT was performed by series of isolated pulses in a laboratory unit operating on the basis of capacitor batteries [2]. The battery discharge was transmitted by means of the copper electrode touching the treated surface, and the contact wire was fastened at the edge of the specimen gauge. After EDT completion polishing and heat treatment of the metal surface was conducted that provided an accurate LL pattern.

In this work LL distribution in specimens of low-carbon St3 steel under the conditions of their longitudinal tension was studied. From [3] it is known that at treatment by current discharges of pre-strained specimens the deformation resistance discretely decreases in the metal, which is manifested in the form of characteristic load dropping in σ–ε stress-strain curve (here, σ is the tension, ε is the relative deformation).

Testing was performed in TsDM-10 tensile testing machine with up to 100 kN tensile force at 6 mm / min straining rate. Continuous recording of the change of the tensile force up to the moment of the specimen reaching the yield point (necking) or its failure was conducted during the entire loading cycle. Patterns of LL distribution over the metal surface were recorded at different stages of loading and treatment by current pulses. With this purpose the specimen was fixed in

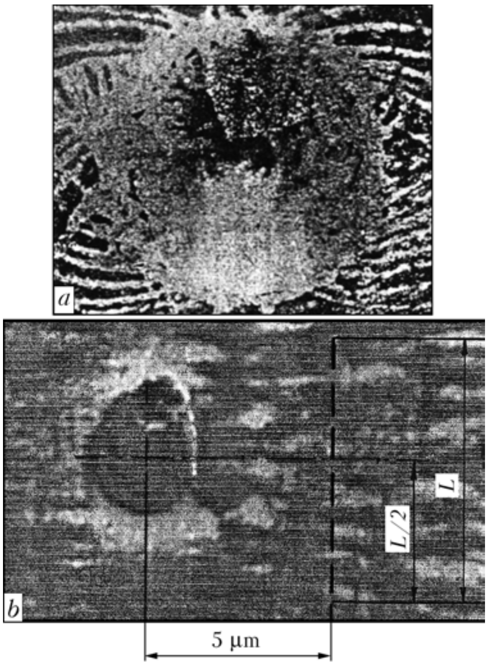

Figure 1. LL patterns obtained at mechanical (Erickson sample) (*a*) and electrodynamic (*b*) impacts: dashed line — line of measurement of band profilegrams

the grips of the testing machine, stretched up to the specified length and EDT by a series of current pulses was conducted with recording of the deforming force change and LL patterns. At pulsed treatment of specimens from steel St3 the following parameters of EDT mode were used: maximum electrode voltage U_e = = 480 V; maximum electrode current I_e = 2500–3200 A; pulse duration t_p = 0.00065–0.00084 s; capacitor bank capacity C = 4400 μF.

EDT mode parameters were calculated proceeding from the need to induce more noiticeable plastic deformations in the specified material volume with yield limit σ_y due to conversion of electric energy into mechanical energy. The energy discharge of the capacitor bank of about 1000 J power induces plastic deformations in low-carbon steel 3–4 mm thick, the presence of which is indicated by LL formation. This is quite admissible, considering that inducing in steel volume of 1 mm^3 with yield point σ_y the deformation equal to $\sigma \sim K\sigma_y / E$ requires its potential energy to be equal to [4]

$$A = \frac{\sigma_y^2 \xi^2}{E}, \qquad (1)$$

where $K \cong 3$–5 and $\xi > 1$ are the coefficients allowing for the material straining rates up to σ_y values; E is the material modulus of elasticity. Taking σ_y = = 280 MPa, $E = 2{\cdot}10^5$ MPa, $K = 5$, $\xi = 2$, we obtain $A = 7.84{\cdot}10^{-3}$ J / mm^3. Accordingly, at energy losses of 1000 J, allowing for the coefficient of losses η at transformation of electric energy into mechanical energy volume V of plastic deformation is equal to

$$V = \frac{1000\eta}{A} = 1.27{\cdot}10^3\eta \ [\mathrm{mm}^3]. \qquad (2)$$

At the thickness of studied samples δ = 4 mm the area of plastic deformation zones is equal to

$$S = \frac{V}{\delta} = 3.2{\cdot}10^4\eta \ [\mathrm{mm}^2], \qquad (3)$$

and linear dimensions of the plastic deformation field

$$\sqrt{S} = 180\sqrt{\eta} \ [\mathrm{mm}], \qquad (4)$$

which at reasonable η values is close to the data derived by us experimentally.

Formation of LL patterns was studied in the base metal and butt welded joints. The welds were made manually using coated electrodes of 4 mm diameter of ANO-4 grade in the following deposition mode: arc voltage U_a = 70 V, welding current I_w = 150 A, welding speed v_w = 5 / h.

At the initial stage of investigations LL patterns at the mechanical and electrodynamic impact on low-carbon steel were compared. For this purpose polished samples of one series were subjected to static loading by indentation of a sphere (Erickson sample) [5], and those of the other — to electrodynamic impact by an isolated current discharge in the above mode (Figure 1). Both loading modes are characterized by a local application of the load, i.e. point contact of the working tool (sphere or electrode) with the surface being treated. In addition, in both the cases a high intensity of pulsed action (mechanical or electrical) is in place, which may lead to development of local yield zones in the contact point, i.e. local zones of plastic deformation with a high gradient, which are located near the point of contact of the working tool with the sample surface.

Analyzing LL patterns given in Figure 1, it can be seen that the geometrical characteristics of the bands at point mechanical impact differ from those observed at EDT. At sphere indentation LL take the shape of an ellipsoid (Figure 1, *a*), the diameter of which is comparable with that of an imprint, which is indicative of a high concentration of the local yield zones at point mechanical loading of low-carbon steel.

A different pattern of band distribution is observed at an isolated pulsed current discharge (Figure 1, *b*). In this case LL are a system of mutually parallel bands spreading out on both sides of the contact spot. While at sphere indentation LL concentrate in the imprint zone, at EDT they cross the entire cross-section of the joint. Different LL systems forming in welding and cooling of low-carbon steel were studied in [6, 7], in which the bands similar to those shown in Figure 1, *b*, are classified as transverse.

We have conducted studies on taking the profilegrams along the specimen longitudinal axis on its face and reverse surfaces in the pulsed action zone (electrode contact). Measurements were taken before and after EDT using a special arm fitted with an indicator head with division value of 1 μm. Profilegrams of the specimen surface, which are the difference of values of band height h obtained from instrument readings at EDT, are shown in Figure 2.

Measurements showed that residual shape change of the specimen surface in the treatment zone of length L (Figure 1, *b*) becomes wave-like. The wave-like shape of the profilegrams from both sides of the specimen is indicative of the fact that current pulse treatment of the entire cross-section and not just the metal surface was performed.

At the first stage of investigations of the features of formation of the plastic deformation fields at EDT the flat ground blade-type specimens from St3 steel were loaded stepwise by uniaxial tension σ (Figure 3). Specimen tension up to the specified length was performed in stages with soaking for 12--15 min. The polished surface of the metal was visually examined and LL appearance was recorded. Comparing LL pattern with the respective loading level leads to the conclusion that the process of LL formation starts at σ = 280 MPa (Figure 3, *a*) in the concentrator zones at the edges of the specimen gauge. The bands are oriented at an angle of 45° to the loading line. After tension up to σ > 300 MPa (necking) and loading interruption (Figure 3, *b*) active plastic flowing of the metal occurs over the entire specimen gauge, which is characterized by a developed LL system oriented at different angles to the load line. Comparing LL pattern at the specimen neck, i.e. in the zone of active plastic flow of the metal corresponding to prefracture, with those obtained at EDT (see Figure 1, *b*), one can see the similarity of their geometry.

At loading of base metal specimens with concurrent EDT, the processes of formation of plastic deformation fields started at lower levels of tensile stresses compared to the variant shown in Figure 3. At specimen tension up to 190 MPa with subsequent EDT, σ values dropped to 110 MPa after three current pulses, and transverse LL formed on the polished surface of the metal (Figure 4, *a*). A higher density of the lines was found in the zones of the pulsed action and contact wire fastening on the specimen, which is indicative of an intensive plastic flow of the metal localized in the electric contact zones.

It should be noted that the process of plastic deformation development on specimens from steel St3 without EDT starts at tensile loads 2 times higher than at current pulse treatment. At sample reloading up to σ = 230 MPa followed by EDT, σ values drop to 140 MPa is found, which is accompanied by development of transverse LL, their densification at the contact zone and appearance of inclined bands oriented at an angle of 45° to the load line (Figure 4, *b*). After EDT and sample tension to σ = 250 MPa LL concentration increases. Appearance of bands of different orientation is observed (Figure 4, *c*). Comparing LL obtained at σ = 250 MPa (Figure 4, *c*) with concurrent EDT and those presented in Figure 3, *a* (σ = 290 MPa) one can see the difference in their formation. If at loading without EDT up to 290 MPa the initial stage of the process of formation of the local plastic deformations (see Figure 3, *a*) is observed, then in the case of EDT application already at σ = 200 MPa (see Figure 4, *c*) plastic deformation of the sample gauge part develops, which is close to that observed at material fracture (Figure 4, *d*). Tensile stress-strain curve σ–ε of the sample from steel St3 at EDT is shown in Figure 4, *e*.

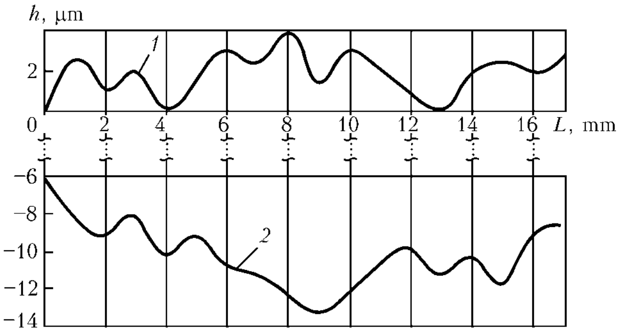

Figure 2. Profilegrams of face (*1*) and reverse (*2*) surfaces of the specimen at EDT

Local plastic flow of the metal at uniaxial tension of welded joint specimens (Figure 5, *a*) starts at σ = = 230 MPa, which is 20 % lower than at base metal loading (see Figure 3, *a*). The process of LL formation proper was of a more intensive nature, and the bands had different orientation relative to the loading line. At increase of σ values up to 270–280 MPa further development of LL occurred (Figure 5, *b*), their intensity increased in proportion to load increase up to necking (Figure 5, *c*). The nature of formation of plastic deformations is close to that found in base metal specimens (see Figure 3, *b*). Under the current pulse impact in the welded joint specimens, unlike the processes shown in Figure 5, *a*, the plastic flow started at specimen tension in the elastic region up to

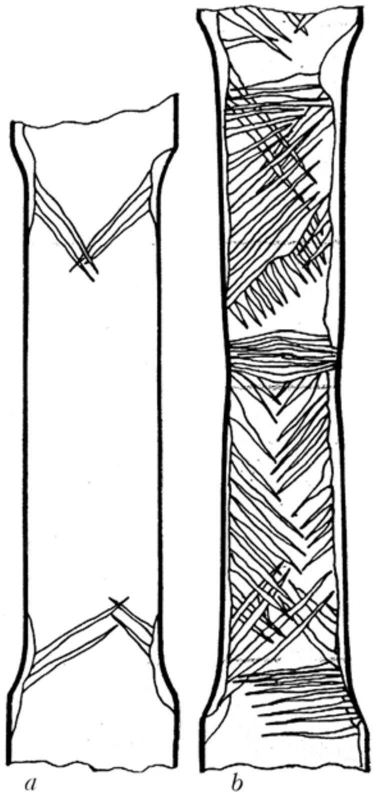
Figure 3. Typical LL patterns formed in specimens of steel St3 at uniaxial tension: *a* — σ = 290; *b* — 320 MPa

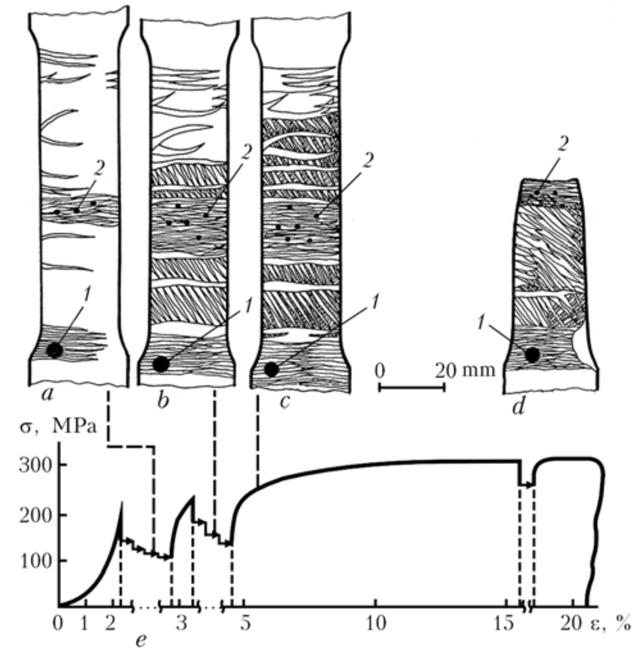

Figure 4. LL patterns formed in specimens of steel St3 at EDT at uniaxial tension: *a* — up to σ = 190 MPa after three current pulses; *b* — σ = 230 MPa after two current pulses; *c* — up to σ = 250 MPa after an isolated current impact; *d* — after fracture; *e* — σ–ε stress-strain curve of specimens from steel St3 at concurrent EDT; *1* — point of fastening the contact wire; *2* — zone of electrode contact with the specimen at EDT

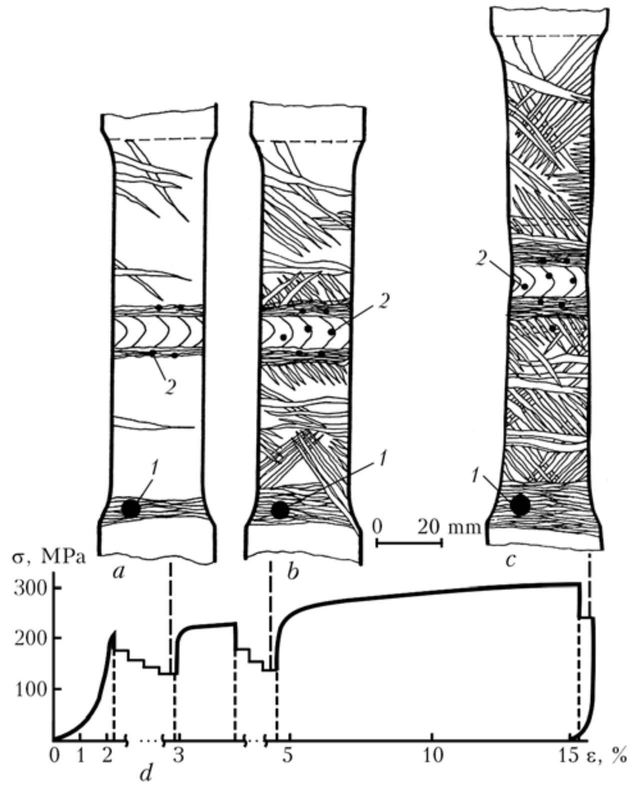

Figure 6. LL patterns formed on specimens of welded joints of St3 steel at EDT under the conditions of uniaxial tension: *a* — σ = = 200 MPa after four current pulses; *b* — σ = 240 MPa after three current pulses; *c* — before fracture after an isolated current pulse; *d* — σ–ε curve of welded joints of St3 steel at concurrent EDT; *1, 2* — same as in Figure 4

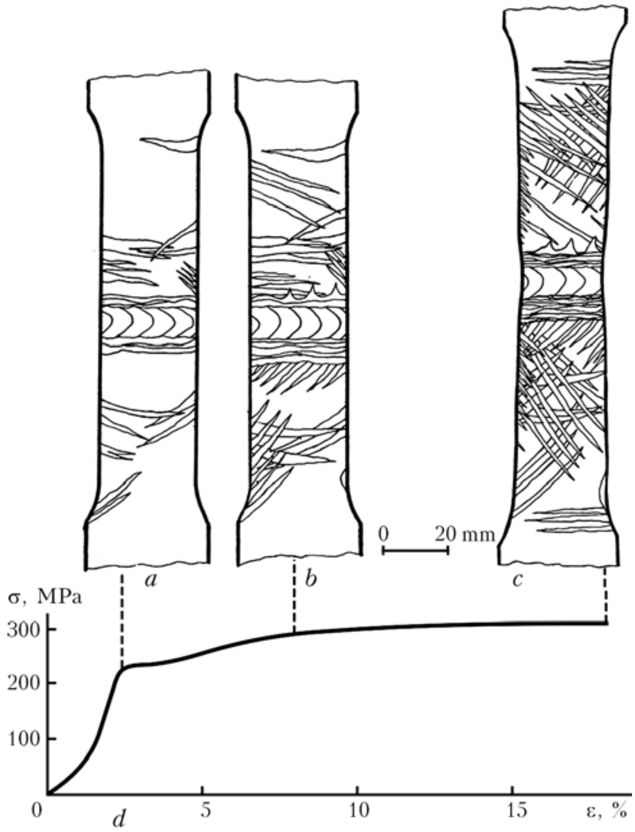

Figure 5. Typical LL patterns formed on the surface of specimens of welded joints of St3 steel at uniaxial tension: *a* — σ = 230 MPa; *b* — σ = 280 MPa; *c* — prefracture region (necking); *d* — σ–ε curve at tension of specimens of St3 steel

200 MPa and load decrease to 120 MPa after four current pulses (Figure 6, *a*). At reloading up to 240 MPa and after three current pulses (Figure 6, *b*) the intensity of LL formation is much higher than at the same load levels, but without EDT (see Figure 5, *b*). At specimen tension up to necking and at application of subsequent individual current pulses, the density of bands of different orientation on specimen surface is higher at EDT than at tension without treatment (Figures 6, *c* and 5, *c*, respectively).

On the whole, comparison of LL of specimens of base metal and welded joints of St3 steel at EDT and without it, allows revealing several features of the studied variants of specimen loading. LL formation at tension without EDT starts beyond the elasticity limit of St3 steel, and at current pulse impact — in the elastic loading region. At equal σ values for loading variants with EDT application and without it, the intensity of plastic flow (band frequency) is higher in the case of current pulse impact. It can be seen at comparison of Figures 5, *b* and 6, *b*. At the stage of prefracture, i.e. necking, a more intensive development of earlier formed bands is observed at EDT compared to specimen tension without current impact (see Figures 5, *c* and 6, *c*). Thus, visual confirmation was obtained of the fact that current pulses lead to formation of plastic flow zones in low-carbon steel welded joints. A combination of plastic deformations developing as a result of EDT with plastic deformations from welding determines the stress-strain state of the welded structure as a whole.

In order to confirm the influence of electrodynamic effect on the change of the stressed state in sheet steel welded joints, EDT of 500 × 500 × 3 mm plates with a longitudinal butt weld located in the center, was performed. To reveal LL polishing of the surface of the assembled specimen edges was performed before welding. The width of the polished layer was 40 mm, which corresponds to half-width of the zone of plastic deformations of a butt weld.

Presence of longitudinal RS was determined by non-destructive ultrasonic testing based on the dependence of the velocity of ultrasonic wave propagation on stresses in the metal [7]. This method allows activisation of the stressed state of the object without violation of its integrity. Longitudinal RS σ_x in the plate were determined after the start of welding, then after EDT. Measurements were taken in the specimen central cross-section, and EDT was performed in the mode described above.

At the moment of EDT the plate was in the free state, i.e. without application of static loads. EDT was performed by point impacts on the weld metal in the direction from its middle to the edges with 90–100 mm step.

In the pattern of LL formed after plate welding, a distribution of bands of different systems typical for a butt weld, including the transverse bands, was observed (Figure 7), their development being related to formation of stresses exceeding the yield point of steel St3 [6]. After point impact of EDT local regions of developed transverse bands were formed in the weld and HAZ in the zone of contact with the metal surface. Whereas LL from welding are uniformly distributed along the entire weld length, the bands from EDT are concentrated in the points of application of the current pulses.

Results of measurement of longitudinal RS σ_x after welding and subsequent EDT given in [8], are indicative of the fact that the impact by current pulses causes a more than 50 % lowering of σ_x in welded joints of St3 steel.

Data given in this work lead to the conclusion that EDT of welded joints of low-carbon steel leads to formation of local zones of plastic deformation of a high intensity influencing the stressed state of sheet metal structures.

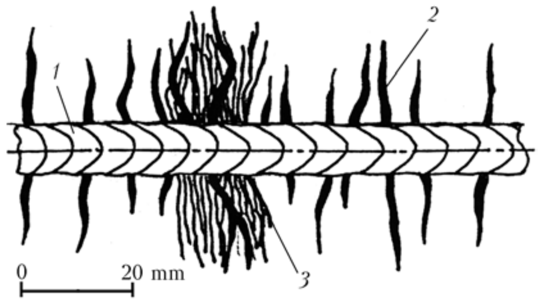

Figure 7. LL patterns obtained on specimens of St3 steel butt joint: *1* — weld; *2* — zone adjacent to the weld after welding; *3* — same + EDT

CONCLUSIONS

1. An experimental procedure has been developed for evaluation of EDT influence on formation of plastic deformations in welded joints of steel St3 based on LL patterns.

2. It is established that treatment by successive current pulses at uniaxial tension of flat samples of the base metal and welded joints of St3 steel causes a drop of the deforming force in the material in the elastic and plastic loading regions, which is accompanied by formation of the characteristic LL.

3. It is established that at EDT at the moment of the capacitor battery discharge a fast conversion of the electric energy into mechanical energy occurs in specimens of St3 steel, leading to formation of plastic deformation fields in the material. If RS develop in the low-carbon steel, at EDT they interact with stresses induced by treatment following the law of continuum deformation mechanics.

4. In full-scale specimens of butt welded joints of St3 steel EDT of the weld causes formation of local plastic deformations in the metal of the weld and HAZ in the form of transverse LL.

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PRINCIPLES OF CALCULATION OF PARAMETERS FOR EXPLOSION WELDING OF LAYERED METAL COMPOSITES

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Principles of calculation and optimisation of parameters for explosion welding of layered metal composites are considered. The energy of plastic deformation of the weld metal at high-velocity collision was selected as a versatile criterial parameter that relates properties of the material being welded to the welding modes.

Keywords: explosion welding, composite materials, optimisation of parameters, multilayer composition

To design technological processes for explosion welding of two- and multilayer composites, it is necessary to select such process parameters which would guarantee production of the welded joints having the required physical-mechanical properties and containing no defects. In this case, parameters of the kinematic group (v_c, v_{con}, γ) that depend upon the setting parameters (h, H, C, m_1, m_2) (Figure 1) should create such conditions (p, τ, ε, T) within the joining zone, under which a sound welded joint is produced.

The purpose of this study was the development of the basic principles of calculation of parameters for explosion welding of two- and multilayer composite materials to provide production of a strong joint.

Wide theoretical and experimental experience has been accumulated, and analytical relationships between parameters of different groups have been derived up to now. Nevertheless, the task posed has a number of peculiarities, which are stipulated, first of all, by selection of a versatile criterial parameter to relate initial properties of the materials welded to strength of a resulting welded joint. Authors of the hydrodynamic approach [2–4, etc.] suggested that critical collision angle γ_{cr} should be used as such a criterion, as it determines, in fact, position of a lower limit of weldability of a certain pair of metals on coordinates γ–v_{con}. In this case, to produce a full-strength joint, it is necessary to meet condition $\gamma > \gamma_{cr}$ at $v_{con.cr} < v_{con} < c_0$ (here γ is the dynamic collision angle, $v_{con.cr}$ is the critical contact velocity; and c_0 is the velocity of sound in metal).

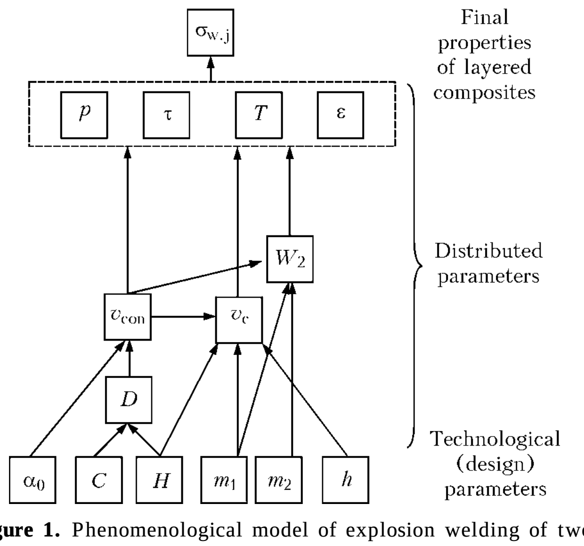

Figure 1. Phenomenological model of explosion welding of two-layer composite [1]: α_0 — setting angle between plates welded; C — content of ammonite in mixture; H — height of explosive charge; m_1 and m_2 — unit mass of flyer and target plates, respectively; h — setting (welding) gap; D — velocity of detonation of explosive; v_c and v_{con} — collision velocity and contact velocity, respectively; W_2 — energy consumed for plastic deformation of weld metal; p, τ, T and ε — pressure, deformation time, temperature and degree of plastic deformation of metal in joining zone; $\sigma_{w.j}$ — strength of welded joint

In the opinion of a number of researchers [5–8], any arbitrary combination of similar and dissimilar materials has a certain critical value of collision velocity, $v_{c.cr}$, that depends upon the yield stress and acoustic stiffness of the metals welded, which, when exceeded, provide a strong joint.

These criterial approaches, differing in form and similar in essence, which ignore such important parameters as mass characteristics or thickness of the elements welded, have a very limited practical application.

It seems that so far the only versatile parameter of this kind, having the physical meaning, is energy W_2, which is consumed for plastic deformation of metals. On the one hand, this parameter relates together collision and mass of the plates being joined, and, on the other hand, it clearly defines the lower limit of weldability depending upon the technological deformability (Astrov criterion HB / δ, which is the ratio of Brinell hardness of metal to its elongation) of metals by the value of critical energy consumption W_{2cr} [1, 9, 10].

It should be noted that, along with W_2 and W_{2cr}, another candidate for a criterial parameter is deformation pulse I_d [11], the values of which characterise the degree of development of plastic deformation of the weld metal and completeness of the activation processes occurring at the boundary of a joint. At present, the use of this parameter is constrained by an insufficient scope of the experimental data for correlation of $I_{d.cr}$ with properties of a wide range of structural materials.

So, allowing for the above-said, consider in detail the basic algorithm of calculation of the process parameters for the simplest case, which is explosion welding of bimetal using the parallel scheme.

At the first stage it is necessary to determine velocity of the contact point, v_{con}, which is usually selected from a range of $(0.4–0.6)c_{0\min}$ [12], where $c_{0\min}$ is the lower velocity of sound in metal of the two ones for a selected combination. As a rule, v_{con} is 2000–2500 m / s. And for a number of compositions, the range of weldability of which is narrow enough (titanium + steel, aluminium + steel, aluminium + copper, etc.), it is recommended to seek the lower limit of the range of the above values.

The next important and critical stage is selection of the type of an explosive. Detailed analysis of properties of explosives is given in studies [4, 13–19, etc.]. Several circumstances should be taken into account for the selection. To simplify the technological process (except for the operations of mixing of components of an explosive prior to welding), the preference should be given to commercially manufactured explosives, e.g. ammonite No.6ZhV, or welding ammonites of the type of A or AT.

The first is a high-capacity explosive with a detonation velocity of $D > 2500$ m / s, which is realised already in flat charges with height $H \approx 12–13$ mm. Hence, it is reasonable to use this explosive for cladding with thin (up to 1.5–2.0 mm) metal layers.

Two other types of ammonites with acceptable ranges of the detonation velocity (1200–3100 m / s) have a very short shelf life, this affecting stability of the detonation characteristics.

In this connection, the fresh mixtures of ammonite No.6ZhV (or its analogues) with ammonium nitrate, quartz sand, sodium chloride, talcum powder or other inert filling agents are utilised in the world practice in the majority of cases to address practical problems. These mixtures are well studied, and their detonation characteristics are available in the form of tables, plots or other empirical dependencies, which, the composition of a mixture being preliminarily selected, are used to determine height of the explosive charge, H, that provides the required detonation velocity, i.e. $D = v_{con}$. For example, the following relationship [1] can be used for a mixture of ammonite No.6ZhV + saltpetre:

$$H = \left(\frac{D}{121.5C^{0.492}}\right)^{3.17}. \qquad (1)$$

Apparent density ρ_{expl} affecting the collision velocity and depending upon the composition of an explosive is also determined for a selected mixture. For a mixture of ammonite with granulated ammonium nitrate, the value of this parameter is very precisely calculated from the following empirical formula [1]:

$$\rho_{expl} = -1.43\cdot10^{-5}C^2 - 1.22\cdot10^{-3}C + 1. \qquad (2)$$

Then the critical value of the energy consumed for plastic deformation, W_{2cr}, is determined for a pair of the materials welded [9]:

$$W_{2cr} = 0.606 + 0.184 \ln (HB / \delta) \ [\mathrm{MJ / m^2}]. \qquad (3)$$

The lower value of the two ones obtained, i.e. corresponding to a softer material in the pair, is selected in this case, and then the minimal required collision velocity is determined by solving the known equation, i.e. component of the energy balance of explosion welding [20]:

$$W_2 = \frac{\rho_1\delta_1\rho_2\delta_2}{2(\rho_1\delta_1 + \rho_2\delta_2)}\, v_c \left[1 - \left(\frac{v_{con}}{c_0}\right)^2\right] \qquad (4)$$

relative to v_c and assuming that $W_2 = W_{2cr}$:

$$v_{c.cr} = \sqrt{\frac{2(\rho_1\delta_1 + \rho_2\delta_2)\, W_{2cr}}{\rho_1\delta_1\rho_2\delta_2[1 - (v_{con}/c_0)^2]}}, \qquad (5)$$

where ρ_1 and ρ_2 are the densities of the material of flyer and target plates, respectively; and δ_1 and δ_2 are the thicknesses of the flyer and target plates of a stack.

In fact, the obtained value of $v_{c.cr}$ determines position of the lower (critical) boundary of welding for the selected pair of the materials with a preset thickness (mass) of the plates.

Given that position of the upper (ultimate) boundary of welding has not yet been determined for the majority of compositions, the certain ΔW_2 value is added to W_{2cr} to estimate ultimate energy consumption W_{2ult}. Normally, ΔW_2 is 0.3–0.5 MJ / m^2 for such pairs of the materials as steel + titanium, titanium + copper, copper + aluminium, aluminium + steel, aluminium + titanium, and some others, while for the other materials characterised by a wide range of weldability this value is 0.8–1.0 MJ / m^2.

Ultimate collision velocity $v_{c.ult}$ is calculated by substituting the value $W_{2ult} = W_{2cr} + \Delta W_2$ for W_{2cr} in (5). In this case, any value of v_c out of the range

$$v_{ñ.cr} < v_c < v_{c.ult} \qquad (6)$$

should provide formation of a full-strength joint in welding.

In an ideal case, the best properties in terms of minimisation of structural and chemical heterogeneities will be exhibited by the joints produced at W_{2cr}. However, when selecting collision velocity v_c from the range of (6), one should by all means bear in mind probable random deviations of the setting parameters from the calculated ones, which may be caused, e.g. by curvature of the plates welded, inaccuracies in assembly of a stack, non-uniform density of an explosive, etc. Preliminary estimates show, in particular, that errors in values h and H amount to no more than 10 % (0.1 mm at a gap of 1 mm). But they may lead to a situation where values W_2 are 15–20 % lower than critical values W_{2cr}. The joint formed in this case will not be a full-strength one. Technological errors have the strongest effect at low values of the h/H ratio [21]. Therefore, to improve reliability of the welding process, the calculations (5) should be based on a value of W_2 that is initially assumed to be 15--20 % higher than the critical value.

So, the value of v_c being selected out of the range of (6), it is not difficult to calculate the required size of the welding gap, h, for the one-dimensional acceleration model:

$$h = H\,\frac{(1-\theta)^2}{(1+2\eta)\theta^2 - 1}, \qquad (7)$$

where

$$\theta = \frac{1 + \eta(1 - v_c/D) + \sqrt{\eta^2(1 - v_c/D)^2 - 2\eta v_c/D}}{1 + 2\eta}; \qquad (8)$$

$$\eta = \frac{16}{27}\,r = \frac{16}{27}\,\frac{\text{Í}\rho_{expl}}{\rho_1\delta_1}; \qquad (9)$$

$$h = \frac{0.184H}{r\left[\dfrac{\left(\sqrt{\dfrac{k+1}{k-1}} - 1\right)\pi}{4\arcsin\left(\dfrac{v_c}{2D}\right)} - 1\right] - 2.71}, \qquad (10)$$

where k is the polytropic exponent of the detonation products [2, 3].

In this case the probability exists that the radical expression in (8) is negative. It means that the selected combination of input data (mixture composition and charge height H calculated for the D value) does not provide acceleration of the flyer plate to the required value of collision velocity v_c. In this case, it is necessary to increase the charge height (in fact, η, which is part, in particular, of (8)) and simultaneously dilute a mixed explosive with inert components to provide the constant value of D.

Compared with determination of parameters for explosion welding of two-layer joints, procedure for calculation of parameters for a case of multilayer compositions is much more complicated. This is associated, first of all, with instability of the collision parameters at boundaries between the layers, and with the necessity to allow for the initial regions of acceleration of the stack after each i-th event of interaction.

Direct calculation of the parameters using analytical dependencies can be made only in one particular case, namely with an assumption that the first flyer plate prior to its collision with the second (intermediate) one is not accelerated by the detonation products (DP), i.e. residual pressure of DP is $p_{res} \to 0$. This situation can be realised at sufficiently high values of the h_1 / H ratio (here h_1 is the gap at the first boundary between the layers of a composite being welded). In this case (after determination of v_{con}), the calculations are made for the critical and ultimate energy consumptions at each interlayer boundary depending upon the mechanical properties of the materials welded, and then, depending upon their values, for the velocity of collision of the first (flyer) layer with the second layer (v_{c1i}^{cr} and v_{c1i}^{ult}), providing the release of energy W_{2i} corresponding to W_{2icr} and W_{2iult}, respectively, at the arbitrary i-th boundary of the composite [1, 10]:

$$v_{c1i}^{cr/(ult)} = \sqrt{\frac{2\sum\limits_{j=1}^{i+1} m_j \sum\limits_{j=1}^{i} m_j W_{2icr(ult)}}{m_1^2 m_{i+1}[1 - (v_{con}/c_{0i})^2]}}, \qquad (11)$$

where i is the index of the collision boundary [1; n -- 1]; j is the index of the layer [1; n); and m is the unit mass of the plate ($\rho\delta$).

The maximal value out of the critical ones and minimal value out of the ultimate ones are determined from the obtained arrays of values of the collision velocity. In this case, meeting the condition of «energy allowability» of the welding process by the simultaneous cladding scheme [1, 10]

$$\max(v_{c1}^{cr}) < \min(v_{c1}^{ult}) \qquad (12)$$

automatically means that at any value of the collision velocity at the first boundary, which is within the above range, and at any boundary between the layers of a composite the value of the energy consumed for plastic deformation of metal will exceed the critical level of the consumed energy required for formation of a strong joint.

Non-meeting inequality (12) means that providing a full strength at all the boundaries of the composite at the said initial conditions will involve problems, as in this case we have the situation where the lower boundary of welding for some i-th collision is above the upper boundary of j-th collision ($i \ne j$). This problem can be solved by two methods: by changing the welding scheme into the opposite one, using the target (lower) plate as the flyer (upper) plate in the stack, the general sequence of the layers in the composite remaining unchanged, or by adjusting the ratio of thicknesses of the layers in the stack.

The first method is simpler to realise. But it is not always suitable, as with changing the sequence of arrangement of the layers the plate of the least ductile material may happen to be used as a flyer plate, which will present additional technological difficulties in terms of preventing its fracture in high-velocity deformation.

Improvement of the energy situation in the stack welded by the second method may be achieved in two ways: either by increasing $\min(v_{c1}^{ult})$ through increasing thickness (mass) of the (i + 1)-th layer, or by decreasing $\max(v_{c1}^{cr})$ through decreasing thickness of the (j + 1)-th layer of a composition (in this case i and j are the indices of boundaries of the stack, which correspond to $\min(v_{c1}^{ult})$ and $\max(v_{c1}^{cr})$).

New values of unit masses of the (i + 1)-th or (j + + 1)-th layer [1, 10] are calculated from the adjusted values of $\min^*(v_{c1}^{ult})$ or $\max^*(v_{c1}^{cr})$:

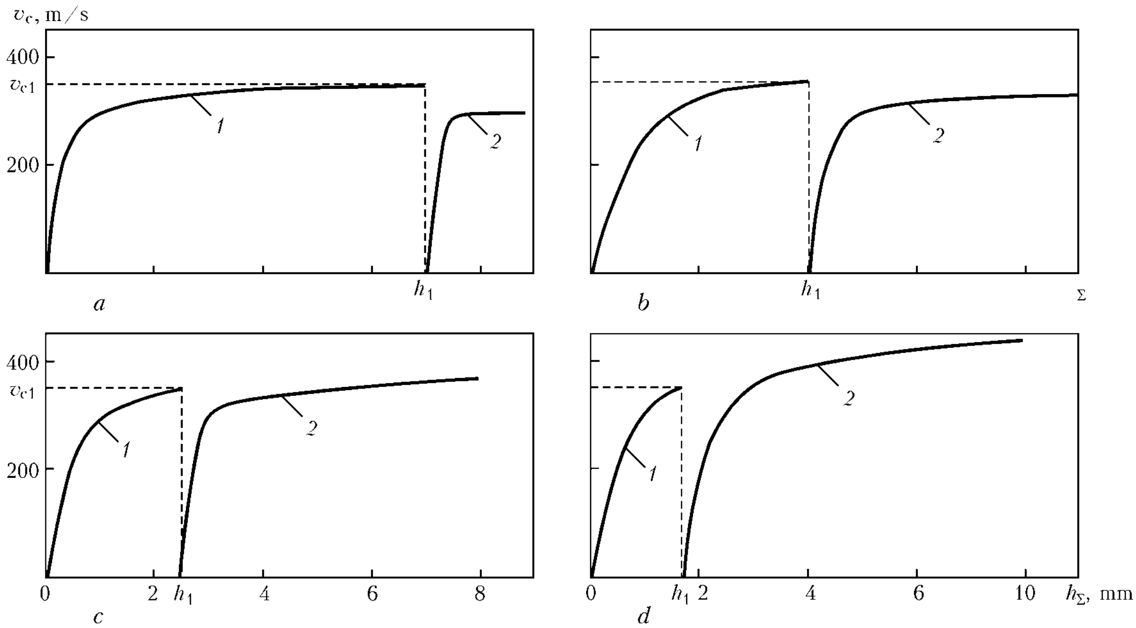

Figure 2. Effect of the phase of acceleration of flyer plate on the collision velocity at the second interlayer boundary in three-layer stack ($\rho_1\delta_1$ = 27 g / cm^2; $\rho_2\delta_2$ = 5.4 g / cm^2; v_{con} = 2500 m / s) at H = 25 (*a*), 30 (*b*), 35 (*c*) and 50 (*d*) mm: *1, 2* — acceleration curves for the flyer plate and stack of two welded plates, respectively

$$A = \frac{W_{2i\mathrm{cr}}}{1 - (v_{\mathrm{con}}/c_{0i})^2}, \qquad (13)$$

where

$$A = \frac{W_{2i\mathrm{cr}}}{1 - (v_{\mathrm{con}}/c_{0i})^2}; \quad B = \frac{W_{2i\mathrm{ult}}}{1 - (v_{\mathrm{con}}/c_{0i})^2}. \qquad (14)$$

They are employed to determine the new values of thicknesses of the corresponding layers in the composite, which are then used in further calculations.

In a more complicated case, where residual pressure of DP still affects the surface of the stack welded after collision of the first two plates, determination of the explosion welding parameters by calculation is an intricate and multi-alternative problem. But unlike the previous situation, where the pressure of DP of a charge tends to zero by the moment of collision of the first (flyer) plate with the second one, and the collision velocity at the second and next boundaries (the stage of initial acceleration being ignored) is unambiguously determined by the value of v_{c1}, in this case the parameters of collision at each interlayer boundary are closely related to each other. Creation of the required conditions for collision at some i-th interlayer boundary is determined by the velocity of collision and stages of acceleration at all the previous boundaries. To illustrate, consider the example of the simplest case of welding of a three-layer composition (Figure 2).

In this example the fixed collision velocity v_c = = 350 m / s at the first boundary can be realised through different combinations of height of the charge (and, accordingly, content of ammonite in a mixture C to maintain a constant detonation velocity) and size of the welding gap h_1 (see Figure 2). Depending upon the phase of acceleration of the flyer plate, h_1 / H, different values of the maximal collision velocity can be achieved at the second boundary: in the example under consideration — from 290 m / s in the case of full acceleration (Figure 2, *a*) to 450 m / s or more at h_1 / H = 0.034 (Figure 2, *d*). In other words, the specified collision velocity at the second interlayer can be achieved, in principle, by using different combinations of parameters of the setting group (H, C, h_1, h_2), i.e. the problem has many design solutions. Considerations for a larger quantity of the layers welded by the simultaneous scheme will be the same.

Given the above-said, the basic algorithm for calculation of the setting parameters is as follows. The explosive detonation velocity is set at the first stage, like for a case of welding bimetal. The experimental or calculated dependencies $D = f(H, C)$ for a selected type of the explosive mixture being derived, it is not difficult to make a two-dimensional matrix of $2 \times n$ combinations of H and C corresponding to a set value of D. Based on the technological considerations, it is reasonable to use standard mixtures (100 / 0, 90 / 10, 80 / 20, etc.).

The ranges of values of the critical and ultimate collision velocities, v_{ci}^{cr} and v_{ci}^{ult}, are then determined from (11) for each interlayer boundary, the values of HB / δ for a material of each layer of the stack welded being preliminarily set.

At the next stage, the values of gaps at the first boundary, providing realization of v_{c1}^{cr} cr and v_{c1}^{ult} at it, respectively, are calculated for each combination of H and C of the earlier developed matrix, thus determining the ranges of the permissible values of H, C and h_1 (Figure 3). Therefore, for the situation shown in Figure 3, the acceptable mixture is ammonite No.6ZhV (not more than 40 vol.%) and granulated ammonium nitrate; and for mixtures 25 / 75, 33 / 67 and 40 / 60 the critical setting gap at the first interlayer boundary (in this case, between titanium δ =

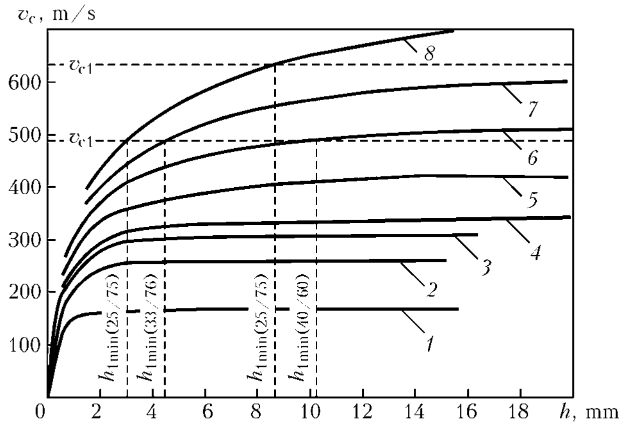

Figure 3. Example of calculation of permissible ranges of setting gaps at the first boundary, h_1, for suitable compositions of the ammonite No.6ZhV / granulated ammonium nitrate (vol.%) explosive mixture in explosion welding of titanium (δ_1 = 5 mm) + aluminium (δ_2 = 2.0 mm) + AMg6 composition: *1* — mixture 100 / 0; *2* — 75 / 25; *3* — 67 / 33; *4* — 60 / 40; *5* — 50 / 50; *6* — 40 / 60; *7* — 33 / 67; *8* — 25 / 75

= 5 mm and aluminium δ = 2 mm), at which the collision velocity corresponding to the critical energy consumption is reached, is h_{1cr} = 3.0, 4.5 and 10.2 mm, respectively.

The ultimate value of h_{1ult} corresponding to ultimate energy consumption W_{2ult} at a collision of the first two layers for mixture 25 / 75 is 8.7 mm (see Figure 3). It is impossible to calculate this value for more saturated mixtures (33 / 67 and 40 / 60 in the example under consideration), as the flyer plate comes to a flat region of acceleration, and further unlimited increase in h_1 does not lead to a marked growth of v_{c1}. In practice, because of the technological considerations, the setting gap is usually limited to 15 mm, and it is this value that is assumed in the given example as h_{1ult} for mixtures 33 / 67 and 40 / 60.

Then, the curves of acceleration of the stack plates are plotted for the second interlayer boundary, $v_{c2} = f(h_2)$, by the procedure described in [22], using a limited array of the H, C and h_1 values obtained at the previous stage of the calculations. Out of the acceleration curves plotted, only those curves which meet condition (6) are left for further consideration, where the corresponding values of h_{2cr} and h_{2ult} are determined for each of them. These operations are repeated for the next interlayer boundaries of a composite being welded.

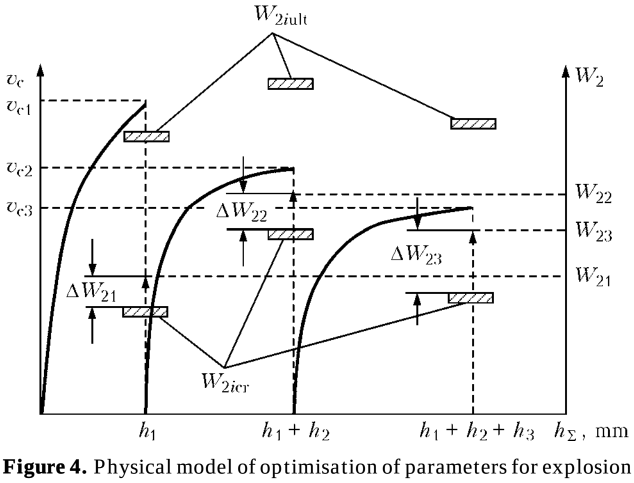

Figure 4. Physical model of optimisation of parameters for explosion welding of multilayer composites [1, 10]: v_{c1}–v_{c3}, W_{21}–W_{23} — collision velocity and energy consumed for plastic deformation of metal at the 1st–3rd interlayer boundaries, respectively; W_{2icr} and W_{2iult} — critical and ultimate energy consumptions at the i-th boundary; ΔW_{21}–ΔW_{23} — difference in actual and critical energy consumptions at the 1st–3rd boundaries of a composite

The calculations made by the said algorithm may result either in none or plenty of design solutions. In the last case, the development engineer chooses one of the obtained arrays of the welding modes, based on his experience and qualification, as well as on the technological capabilities. And in the first case, it is necessary to adjust the input conditions, e.g. change a combination of thicknesses in a composition, or proceed to successive cladding.

To reveal the best design solution out of the plenty obtained, it is necessary to optimise the welding modes, i.e. find those solutions in space of the design parameters (allowing for working limitations), the realisation of which will allow producing a composite with optimal properties, i.e. with maximal possible strength and minimal structural and chemical heterogeneities. In optimisation, the problem of finding a complex set of a large number of parameters of the process studied under conditions of its substantial instability is reduced to minimisation of objective function $M(\vec{X})$. Development of the algorithmic model of the given problem with large dimensions and set limitations is based on the requirement for ensuring such energy inputs at each i-th collision in the multilayer stack, which would be sufficient for formation of a strong welded joint at this boundary.

The most reasonably arranged mode is the mode of layer-by-layer collision in layered composite materials, at which energy input W_{2i} realised at all the boundaries of a composite material is as close as possible to critical energy consumption W_{2icr}, which is characteristic of these boundaries (Figure 4). Apparently, under such conditions the energy input into a system of the colliding plates will be minimal. On the one hand, this minimises the probability of development of structural and chemical heterogeneities at the interlayer boundaries, and on the other hand, this decreases the consumption of an explosive. With such a statement, the optimisation problem is reduced to finding a minimum of objective function $M(\vec{X})$, which is a sum of differences in actual and critical energy consumptions at each i-th boundary of a composite:

$$M(\vec{X}) = \sum_{i=1}^{i=n-1} (W_{2i} - W_{2icr}) = \sum_{i=1}^{i=n-1} \Delta W_{2i} \to \min \quad (15)$$

at the following limitations:

$$W_{2icr} < W_{2i} < W_{2iult}. \quad (16)$$

Main technological (setting) parameters h_1, H and C that determine the $M(\vec{X})$ value at each optimisation stage according to the computer model, which includes the phenomenological and kinematic models, as well as the mathematical tool for calculation of the parameters, can be conveniently taken as design parameters $\vec{X}$.

Considering the productivity of modern computing facilities, the method of random search for design parameters in the *n*-dimensional space, which is a version of the Monte-Carlo method, can be employed to advantage for optimisation [23]. In this case, a set of parameters h_i and H is arbitrarily selected at each optimisation stage using a random-number generator. Then the above parameters are used to calculate the kinematic and energy parameters of the process, as well as the value of objective function $M(\vec{X})$. The first calculated value of $M(\vec{X})$ is chosen as a criterion of minimisation, M, and in subsequent iterations a current value of the objective function is compared with M. If a new value, i.e. $M(\vec{X}) < M$, is obtained, $M = M(\vec{X})$ is reassigned, otherwise the currently calculated variant is screened out. The objective function is thus incrementally improved. It can be expected that the design solution close to a global optimum will be obtained at a sufficiently large number of iterations, amounting to hundreds of thousands.

It should be noted that certain limitations, such as the limitations on critical and ultimate height of the explosive charges, minimum and maximum permissible welding gaps, as well as a number of other parameters, are imposed on the space of the design parameters prior to the optimisation procedure, which substantially reduces the time of calculations and quantity of iterations.

Therefore, the above principles of calculation and optimisation of parameters for explosion welding of layered composite materials, based on the use of the energy consumed for plastic deformation of metal of the weld zone at high-velocity collision as a versatile criterial parameters for relating properties of the materials welded to welding conditions, serve as a theoretical ground for development of a computer model of the process being studied and a corresponding software, which make it possible to considerably reduce the costs of design of technological processes for manufacture of composite materials with the guaranteed quality of joining of the component layers.

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EFFECT OF INITIAL STRUCTURE AND PARTICLE SIZE COMPOSITION OF POWDER ON STRUCTURE OF METAL 10R6M5 DEPOSITED BY THE PLASMA-POWDER CLADDING METHOD

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Effect of initial structure and particle size composition of additive powder PG-10R6M5 on structural state of deposited metal produced by plasma-powder cladding using the above powder was investigated. It is shown that the effect of inheritance of structure of the PG-10R6M5 powder by the deposited metal takes place in cladding: the higher the content of the α-phase in the powder, the higher its content in the deposited metal, the content of the γ-phase decreasing accordingly.

Keywords: plasma-powder cladding, high-speed steel, additive powder, microstructure, particle size composition, deposited metal, structural heredity

Structural heredity in the cladding material--molten pool--deposited metal system may have a dual effect on properties of the deposited metal [1]. Owing to structural heredity, cladding materials may impart to the deposited metal such positive properties as fine-grained structure, uniform distribution of the strengthening phase (carbides, carbonitrides, borides, carboborides), directed orientation of dendrites, etc. At the same time, the negative aspect of structural heredity may also take place in cladding: harmful impurities and non-metallic inclusions may transfer from cladding materials to the deposited metal and, therefore, deteriorate its structure and properties.

The effect of structural heredity shows up to the highest extent with three cladding methods, where the cladding materials are non-conducting, and where there is no strict relationship between the arc current and melting efficiency of a cladding material. One of such methods is plasma-powder cladding. Considerable non-uniformity of heating of a powder (discrete particles) in the plasma arc and the probability that non-melted powder particles may get into the molten pool should have an impact on its size, mass and temperature [2, 3], as well as on the character of solidification, structure and service properties of the deposited metal.

Structural heredity can be controlled by varying composition, structure and shape of the cladding materials, as well as thermal, kinetic and slag (with the cladding methods that use flux) parameters of cladding.

The purpose of this study was to investigate the effect of additive powder PG-10R6M5 of different particle size compositions on structure of the deposited metal produced by the plasma-powder cladding method. The choice of the PG-10R6M5 powder for investigations was based on the fact that it is one of the most common consumables used for plasma cladding of iron-base powders.

Depending upon the design of a plasmatron, additive powders used for cladding may have particles with sizes ranging from 40 to 316 μm (less often — up to 400 μm). As a rule, they are produced by atomisation of liquid metal with inert gas or water.

Structure of the PG-10RM5 powder with a minimal 40–50 μm (Figure 1) and maximal 250–315 μm (Figure 2) size of its particles was investigated. It was established that the powder with particles 40–50 μm in size, which solidifies at a higher rate, has a very fine structure, and can hardly be identified even at the ×2000 magnification (Figure 1, *d*). Dendrites oriented mostly toward the centre of a powder particle in the powder structure, as well as the eutectic component along the grain boundaries can be seen at this magnification.

Structure of the PG-10R6M5 powder with a particle size of 200–315 μm differs from the above one in coarser disoriented grains (Figure 2, *b*). It is close in character to structure of cast high-speed steel 10R6M5 [4]. Precipitates of the eutectic component along the grain boundaries, as well as martensitic needles and retained austenite can be seen at a high magnification (Figure 2, *c*).

X-ray diffraction analysis of the PG-10R6M5 powder of different particle sizes and the deposited metal produced by plasma-powder cladding using this powder was conducted to determine phase composition (Table 1). Whereas the γ-phase is dominant in structure of the powder with fine particles (59.88 %), the powder with coarse particles, on the contrary, contains a larger amount of the α-phase (55.14 %), which consists of martensite and ferrite. Structure of the powder of both particle size compositions comprises no carbide inclusions. Heredity of structure of the powder by the deposited metal is illustrated in Figure 3, which shows

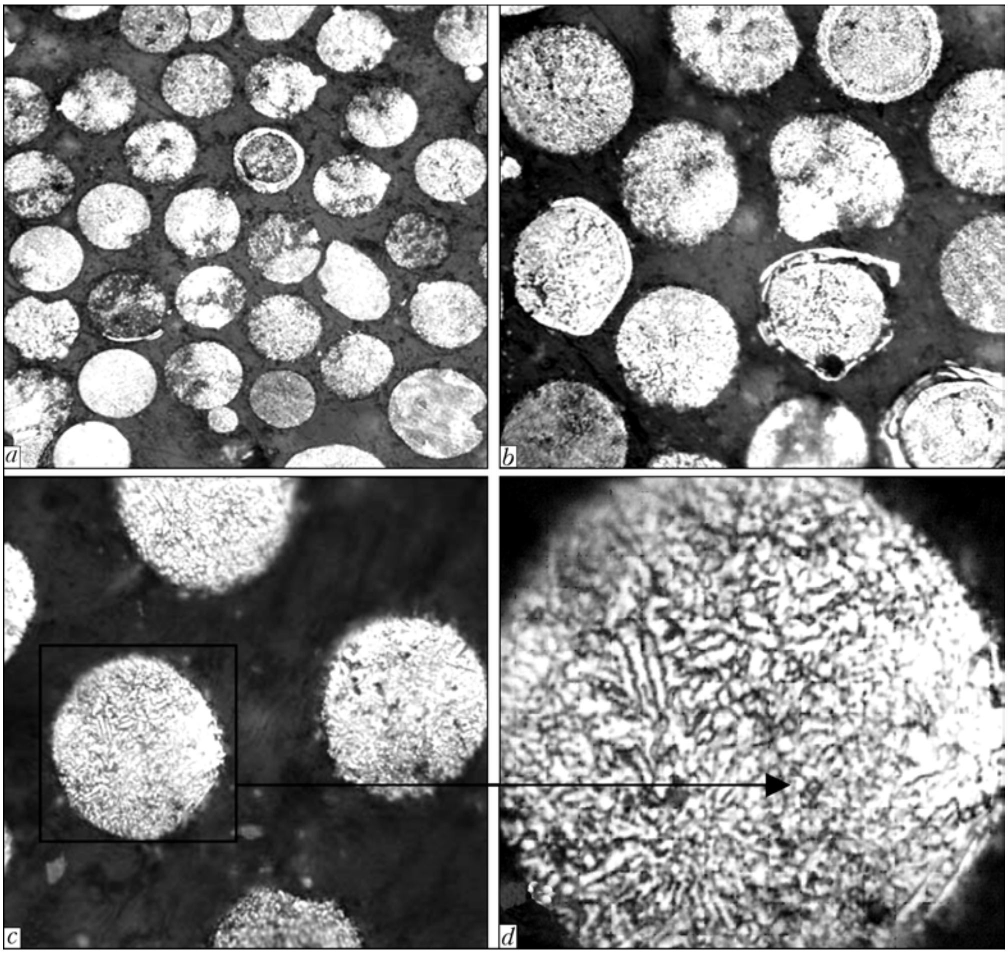

Figure 1. Microstructure of the PG-10R6M5 powder particles 50 μm in diameter: *a* — ×200; *b* — ×400; *c* — ×630; *d* — ×2000 (etching in HNO_3 + HCl + glycerine solution)

X-ray patterns of the powder with a particle size of 40–50 μm and metal deposited with this powder.

The content of the α-phase grows in the deposited metal. But as the content of the α-phase is higher in the powder with coarse particles, its content in the deposited metal produced by using this powder also increases. Carbide inclusions are formed, and their amount is also differing: deposited metal produced by using fine powder particles contains more carbide inclusions.

Based on the content of the α- and γ-phases, the certain inheritance of structure of the powder by the deposited metal can be traced in plasma-powder cladding: the higher the content of the α-aphase in the powder, the higher its content in the deposited metal, the content of the γ-phase decreasing accordingly.

Although the amount of the powder, which can be fed to the plasma arc and melted in it and in the molten pool, depends upon the cladding parameters, this dependence is not direct, as is the case, e.g. of metal-electrode arc cladding. Experiments were conducted to evaluate the effect of plasma cladding parameters on melting of the PG-10R6M5 high-speed steel additive powder of different particle sizes. The

Table 1. Results of X-ray diffraction analysis of powder PG-10R6M5 with particles of different sizes, and metal deposited by using this powder*

Material studied	Particle sizes, μm	Phase composition, wt.% (*a*, nm)		Content of carbides Mo_2C, wt.% (*a*; *c*, nm)
		α-phase	γ-phase	
Powder PG-10R6M5	40–50	40.12 (0.2885)	59.88 (0.3626)	--
Deposited metal — steel 10R6M5	40–50	51.57 (0.2882)	43.36 (0.3610)	5.07 (0.2939; 0.4645)
Powder PG-10R6M5	250–315	55.14 (0.2897)	44.86 (0.3624)	--
Deposited metal — steel 10R6M5	250–315	62.83 (0.2892)	34.45 (0.3623)	2.72 (0.2959; 0.4665)
Note. *a* and *c* — lattice parameters.				

*X-ray diffraction examinations were conducted by Dr. M.V. Karpets (I.M. Frantsevich Institute for Materials Science Problems) and Eng. L.T. Eremeeva (E.O. Paton Electric Welding Institute).

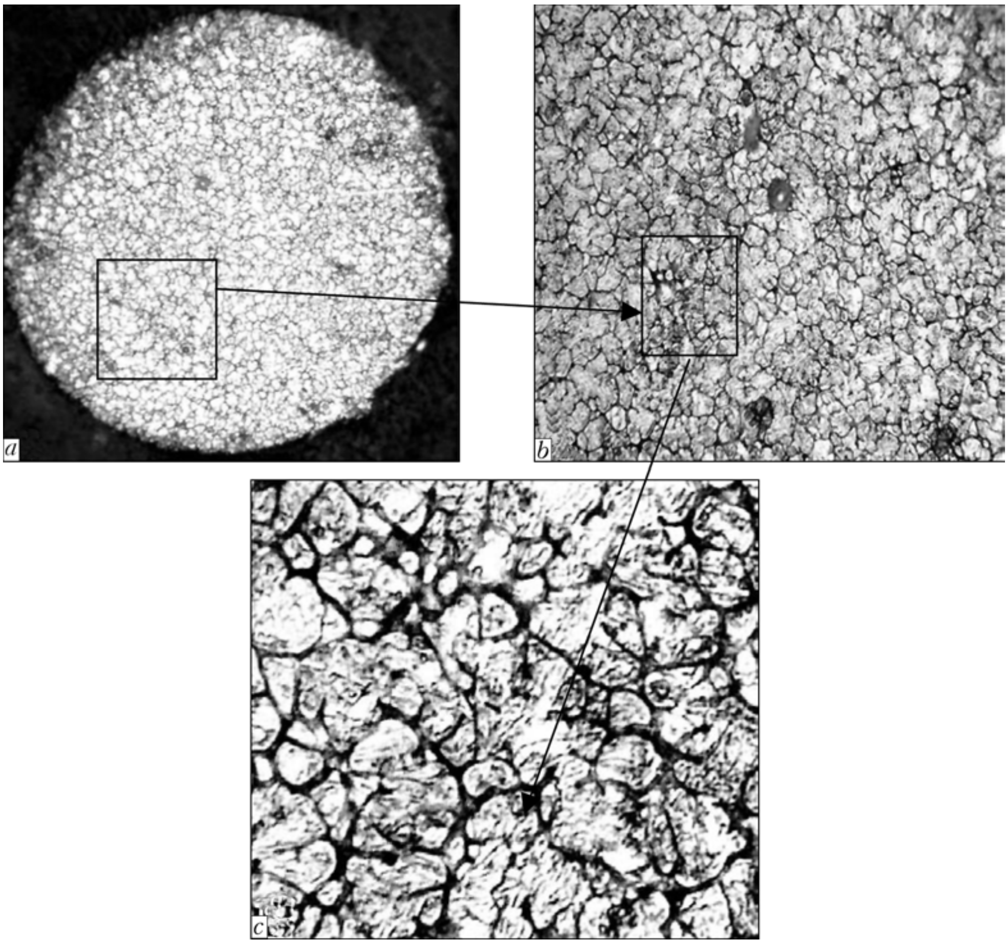

Figure 2. Microstructure of the PG-10R6M5 powder particles 200 μm in size (electrolytic etching in chromium anhydride, U = 7 V, τ = 3 s): *a* — ×320; *b* — ×800; *c* — ×2000

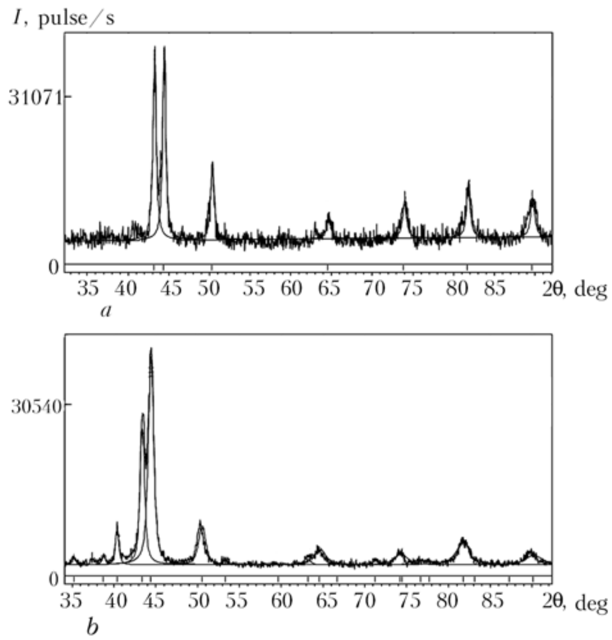

Figure 3. Intensity I of X-ray radiation versus angle of reflection of lines θ characteristic of the said structural phases in powder PG-10R6M5 with 40--50 μm particle size (*a*) and metal deposited by plasma-powder cladding using the said powder (*b*)

experiments showed that increase in the amount of coarse particles in the additive powder makes it necessary to increase the cladding current (Figure 4). Curve *1* in this Figure was plotted for powders of the following particle size compositions, μm: 40–63 (mean particle diameter d_{mean} = 50 μm), 80--125 (d_{mean} = = 100), 125–160 (d_{mean} = 140), 160--200) (d_{mean} = = 180), 200--250 (d_{mean} = 225), 250--315 (d_{mean} = 280) and 315–400 (d_{mean} = 360). Curve *2* corresponds to a mixture of powders of different particle size compositions — fine (d_{mean} = 100 μm) and coarse (d_{mean} = = 280 μm) in different ratios.

It is not indicated to use powders with coarse particles ($d_{mean} \geq 360$ μm), as the arc current equal to $I_a > 400$ A is required for their full melting, and the use of this current leads to excessive penetration of the base metal, this having a negative effect on properties of the deposited metal. In the case of using powders with coarse particles, if the current is not high enough, non-melted particles may remain in the deposited metal.

For the powders of a wide particle size composition range, the arc current needed for full melting of all the powder should be much higher than for the powders with a narrow particle size composition range (see curve *2*, Figure 4).

The effect of particle size composition of the powder on shape of the deposited bead (Figure 5) was

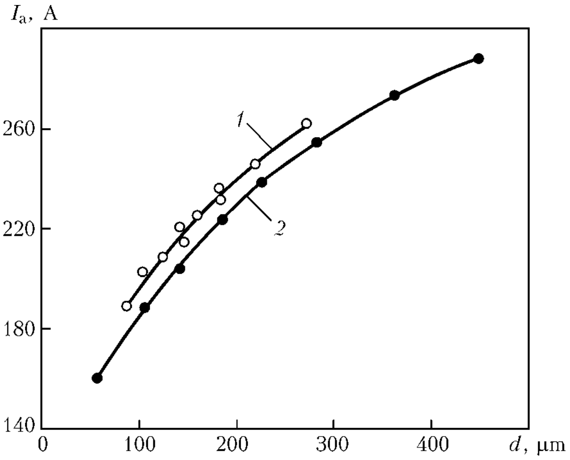

Figure 4. Dependence of arc current I_a of plasma-powder cladding upon diameter d of powder particles melted in the arc: *1, 2* — see in the text

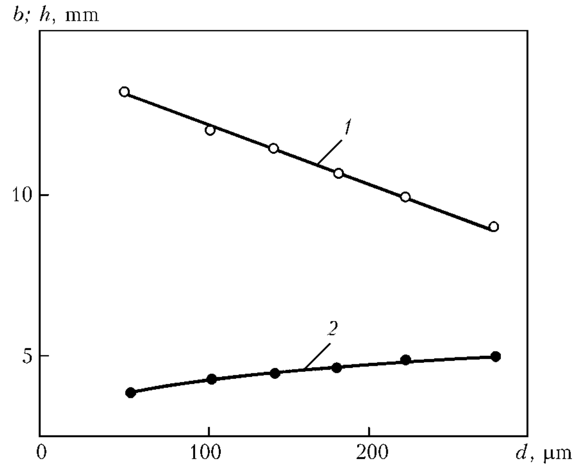

Figure 5. Effect of particle size composition of the powder on width b (*1*) and height h (*2*) of the deposited bead

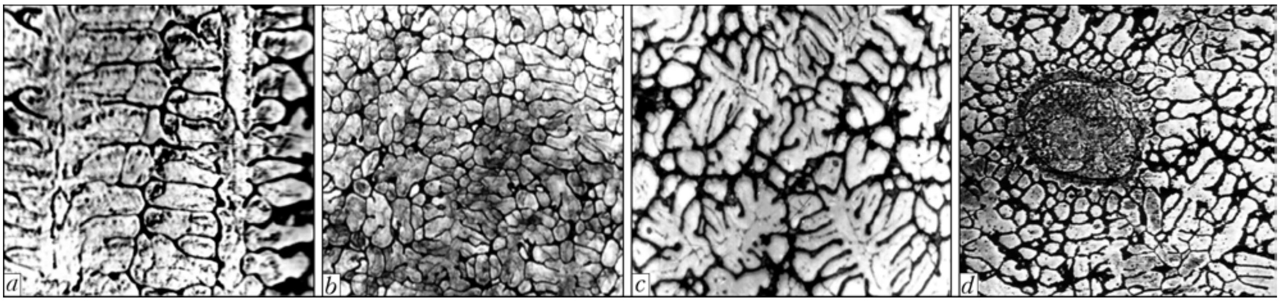

Figure 6. Microstructure of deposited metal 10R6M5 produced by adding coarse particles to fine particles of the additive powder: *a* — mixture No. 2; *b* — No. 3; *c* — No. 4 (see Table 2); *d* — non-melted inclusion (×400)

experimentally evaluated under the following cladding conditions: arc current 240 A, cladding speed 12 m / h, and powder feed speed 4.2 kg / h. The arc current being the same, width of the bead decreases, and its height increases with increase in size of the powder particles, i.e. the bead becomes narrow and high, which is undesirable for cladding.

Plasma cladding of high-speed steel samples using the PG-10R6M5 powder (cladding speed 12 m / h, powder feed speed 4.2 kg / h) was performed to investigate the effect of particle size composition of the powder on structure of the deposited metal. The additive powder consisted of a mixture of fine (40–125 μm) and coarser particles in different proportions (Table 2).

Addition of 15 % of the coarser-grained powder to the fine-grained one caused no special changes in its structure (Figure 6, *a*). At an approximately 30 % content of coarse particles with a size of 200–250 or 315–400 μm (see positions 3 and 6 in Table 2), structure of the deposited metal becomes markedly refined, and the carbide network becomes very fine (Figure 6, *b*).

With further increase of up to 45 % in the content of the above particles, structure of the powder retains its mostly disoriented character, but coarser dendrites are formed, growing toward the solidification centres. The latter are coarse powder particles, which are fully melted in the molten pool (Figure 6, *c*). If such particles have no time to be completely melted, they act as the solidification centres (Figure 6, *d*).

Table 2. Effect of additions of coarse powder particles on structure of metal of the deposited beads (main range of particle sizes — 40–125 μm)

No.	Content of additive (wt.%) with particle sizes		I_a, À	Characteristic features of structure
	200–250 μm	315–400 μm		
1	–	–	205–210	Dendrites of different length, oriented in one direction
2	15	–	210–215	Same
3	30	–	215–220	Disoriented fine dendrites and fine network of carbides along grain boundaries
4	45	–	220–225	Fine and coarse dendrites oriented toward the solidification centre
5	–	15	215–220	Dendrites of different length, oriented in one direction
6	–	30	220–225	Disoriented fine dendrites and fine network of carbides along grain boundaries
7	–	45	225–230	Fine and coarse dendrites oriented toward the solidification centre

The character of the effect on structure of the deposited metal by coarse particles of both size ranges is almost identical. However, at a high (≥ 45 wt.%) content of particles of the 315–400 μm size range, the deposited metal contains much more particles that remain non-melted.

Therefore, as shown by the metallographic examinations, coarse particles in plasma-powder cladding may act as extra solidification centres. Their effect is similar to that of an extra additive material in the form of granules, which are added to the weld pool in submerged-arc welding.

CONCLUSIONS

1. X-ray diffraction analysis showed the effect of structural heredity of the initial structure by the deposited metal, taking place in plasma-powder cladding using the PG-10R6M5 powder as an additive: the higher the content of the α-phase in the powder, the higher its content in the deposited metal, the content of the γ-phase decreasing accordingly.

2. Cladding using mixtures of powders with a wide particle size composition range requires a much higher current to fully melt the powders, compared with cladding using powders with a narrow particle size composition range.

3. Metallographic examinations show that in plasma-powder cladding of powders with fine particles (40–125 μm), structure of the deposited metal consists of coarse dendrites oriented in a direction of heat removal. Addition of 30 wt.% of coarse particles (200–250 or 315–400 μm) to the PG-10R6M5 fine-grained powder leads to formation of additional solidification centres and refining of structure of the deposited metal. With an increase of up to 45 wt.% in the content of coarse particles, the non-melted particles of the additive powder may remain in structure of the deposited metal.

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PRODUCTION OF WELDING CONSUMABLES IN CIS (on the basis of materials of the IV International Conference on Welding Consumables of CIS Countries)

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On 18–21 of June 2007, the «Elektrod» Association of enterprises of CIS countries has held jointly with SPC «Welding Consumables» (Krasnodar, RF) IV International Conference «Welding Consumables. Development. Technology. Production. Quality. Competitiveness» in settlement Agoj, Krasnodar region.

Heads of enterprises and joint-stock associations, leading scientists, process engineers, and designers took part in work of the conference. According to their kinds of activity participants (71 persons) of the conference from Russia and Ukraine represented design engineers, producers, consumers of the welding materials and technological equipment, and suppliers of the raw material components. There were five doctors of sciences, academician of IARE and seven candidates of sciences among the participants. I.M. Livshits, president of the «Elektrod» Association («Instrel» Ltd, St.-Petersburg) acted as moderator of the conference.

The reports, presented at the conference, were included into the collection of reports, which was published by the beginning of its work and distributed among the participants.

Director-general of SPC «Welding Consumables» Ltd. V.M. Dzyuba, chairman of the Krasnodar region Administration N.N. Makrushan, president of RSTWS O.I. Steklov and director of Moscow department of RSTWS V.K. Belyaev addressed the participants with welcome speech. Greetings from the team of employees of the E.O. Paton EWI and its director, academician B.E. Paton, and director-general of CRDI of SM «Prometej», academician I.V. Gorynin were read. In the greetings constant care of the association of improvement of the national production of welding materials under conditions of bitter competition and expansion of the imported products was noted. The association makes a consolidation contribution into co-operation of specialists of the CIS countries in the field of welding materials, initiates discussion of urgent scientific and industrial problems, and helps to solve a great number of topical issues.

Executive director of the association P.V. Ignatchenko analyzed state of production of welding materials in CIS countries in 2006 and noted that the enterprises, which are its members, ensured a lion's share of produced in CIS welding materials. By now

the problems of packaging of the welding electrodes, solid and flux-cored wires are practically solved. Commercial production of the alloyed coppered wire with a row winding on cassettes of different mass is started; piece marking of the electrodes is performed. Management of the association undertook on the eve of the conference one more attempt to collect from the enterprises-consumers of the welding materials information on the claims against suppliers of different, as a rule, certified materials. Unfortunately there was no any response. Then P.V. Ignatchenko dwelled upon volumes of production of the materials.

In 2006 in CIS countries 120 mill t of steel and 99 mill t of rolled metal were produced (in Russia these production figures constituted 71 mill t of steel and 58 mill t of rolled metal). Increase in comparison with 2005 made up: for steel 9.4, for rolled metal 6.6 %. Ukraine produced 41 mill t of steel and 34 mill t of rolled metal. The increase made up: for steel 6.2, for rolled metal 3.8 %.

General volume of production of the coated welding electrodes in 2006 in the CIS countries made up 324.7 thou t, 78.6 % of which were produced at the enterprises of Russian Federation, 16.8 % in Ukraine, and 4.6 % in the rest CIS countries. Last year general volume of production of the electrodes increased in comparison with 2005 by 6.1 %, in Russian Federation this increase being 6 and in Ukraine 4.4 %. Volume of production of the electrodes by types of the coatings constituted 183.4 thou t with rutile-ilmenite coating and 118.7 thou t with base coating. Production of special-purpose electrodes for welding of high-alloy steels and non-ferrous metals constituted 22.6 thou t.

All together 255.6 thou t of electrodes were manufactured in Russian Federation, including with rutile-ilmenite coating — 128.9 thou t, with base coating — 104.8 thou t, special electrodes — 21.9 thou t. In Ukraine 53.9 thou t of electrodes were manufactured, including with rutile-ilmenite coating — 41.4 thou t, with base coating — 11.8 thou t, special electrodes — 0.70 thou t.

Positive trend of increased production of the electrodes of small and medium diameter (2.6–4.0 mm) began to show. Their total production constituted 278.4 thou t, increase in comparison with 2005 made up 3 %. Production of the electrodes of 5.0 and 6.0 mm diameter constituted 46.1 and 1.2 thou t respectively. So, 85 % of the produced electrodes were the ones of up to 5.0 mm diameter. General production volume of the alloyed welding wire of up to 2.0 mm diameter for mechanized gas-shielded welding constituted 46.4 thou t, of which 27.7 thou t were of 0.8–1.4 mm diameter. In Russian Federation 35.1 thou t of the wire were produced, 22.4 thou t of which were of 0.8–1.4 mm diameter, and in Ukraine — 11.3 thou t, 5.3 thou of which were of 0.8–1.4 mm diameter.

General volume of the welding wire production increased in comparison with 2005 by 2.6 %; in Russian Federation this increase made up 5 %, while in Ukraine production remained at the same level. Positive growth of production of the welding coppered wire, quality of which corresponds to materials of leading foreign companies and which is supplied in necessary amounts on pirns and coils with row winding from 3 to 15 kg mass or more, should be especially emphasized. Main suppliers of such wire are enterprises-members of the association: «Mezhgosmetiz-Mtsensk», «MMK-Metiz», Cherepovets, Oryol and Volgograd plants, «Severstal-Metiz» and «Arcsel» companies.

In 2006 there were produced 5953 t of welding and surfacing wires, of which 1961.8 t constituted welding wire and 3992 t surfacing wire, including 200 t of the flux-cored strip. The growth made up 35 % in comparison with 2005. Volume of the flux-cored wire production made up in Russian Federation 4784.6 t, including 1602.6 t of welding wire and 3182 t of surfacing wire. In Ukraine 1169.2 t of flux-cored wire were produced: 359.2 t of welding wire, 610 t of surfacing wire, and 200 t of strip. Increase of the flux-cored wire production in Russia in comparison with the year 2005 made up 61 %, while in Ukraine the opposite trend was observed — the production reduced by 16 %.

Production of welding fluxes constituted 38.7 thou t in 2006, including 10.3 thou t in Russian Federation, 6082.8 t of which was ceramic flux, and in Ukraine — 28.4 thou t. General volume of the welding flux production increased in comparison with 2005 by 2.3 %. Volume of the welding flux production in comparison with 2005 reduced in Russia by 12 %, while in Ukraine it increased by 12 %.

In 2006 general volume of production of the welding materials constituted 415.7 thou t, including for mechanized welding 91 thou t. The share of production of the materials for mechanized welding constitutes 22 % of general production.

One can see from presented data that the main share of welding operations in the CIS countries is performed by coated electrodes. But despite present low level of mechanized welding use the situation gradually improves.

As a whole both Russia and Ukraine have sufficient production capacities for production of welding materials for both manual and mechanized welding. However, because of slow growth of production of the industrial products existing capacities are underloaded. Because of this reason stopped, unfortunately, its existence a big electrode workshop (production capacity 60 thou t) at Cherepovets plant of «Severstal-Metiz» company. Production of electrodes was transferred to Oryol plant of «Severstal-Metiz». It is paradoxical, but despite underload of the existing capacities new production sites for manufacturing of the electrodes continue to be established.

All together about 50 reports and pieces of information were presented at the conference, which reflected results of scientific and engineering works connected with development of new grades of welding materials, samples of the technological equipment, improvement of production of the materials, increase of their quality and competitiveness, state of the issues of certification of the products and quality control, and re-equipment of the existing capacities with state-of-the-art equipment. The reports were presented by companies «Spetselektrod», «Prometej», Izhora branch of «Instrel», «Welding Consumables», «Strojtransgaz», Donskoj STU, «ITS», «Mezhgosmetiz-Mtsensk», «Tekhnoprom», «Ferrosplav», «VNIIST», «Sychevsky electrode plant», «Sozim», «Kubangazstroj», «MMK-Metiz», «ELZ», «Svama», «Roteks», Oryol plant of «Severstal-Metiz» (Russia), E.O. Paton EWI, Electric Machine Building Plant «SELMA», E.O. Paton EWI Pilot Plant of Welding Consumables, «Velma», and «Veltek» (Ukraine).

Among the reports, not included into the collection, the following feature should be noted.

N.B. Korablyov, engineer of «Severstal-Metiz», informed on the changes, which took place in activity of the company within last years. The company was established in 2004 by merger of three plants: «ChSPZ» (Cherepovets), «OSPAZ» (Oryol), and «Volga-Metiz» (Volgograd). In 2006 it obtained international status due to drawing the contract on purchase of the shares of Ukrainian enterprise «Dneprometiz» (Dnepropetrovsk) and British company «Carrington Wire Limited». Nowadays «Severstal-Metiz» occupies leading position in Russian branch (about 30 % of the market) and is the biggest exporter of hardware from Russia into the countries of Europe (about 53 % of general export volume).

Y.V. Kuskov, chairman of the Board of JSC «Spetselektrod» informed on conceptual directions in activity of the enterprise within last years. The first of them is connected with development and mastering of production of the electrodes-analogues of western producers. So acts in Russia ESAB. When producing electrodes in Russia, it widely uses national trade marks and grades. JSC «Spetselektrod» has intention to act in similar way and has already reserved such trade marks as OB and OK. Secondly, there are plans to develop new grades of electrodes with principally new quality, which are difficult to be duplicated. Hear «Spetselektrod» also relies on available capacities, designed for production of special steels. New electrodes of OZL-300 series, characterized by high profitability, were developed. Thirdly, the fact that market of welding equipment is less competitive than market of welding materials is taken into account. That's why own machine-building capacities are used –– the «Spetselektrod» association loads them with production of welding equipment, first of all power sources of wide nomenclature. A customer is proposed a complex commodity «power source + consumables». It is planned to master new types of equipment, including inverter machinery.

At JSC «Spetselektrod» necessary attention is also paid to participation of all specialists in work of a number of commissions of IIW and EWF. This allows more purposeful working in respect to harmonization of the properties of produced materials with the western market requirements. Taking into account prospects of entrance into WTO, issues of quality and price acquire special actuality. Within recent years «Spetselektrod» managed to find reserves for significant reduction of expenses in production of electrodes and increase of the profit rate. In particular, number of workers at the enterprise reduced from 1.5 to 1.1 thou men. Further reduction of the personnel is suggested with simultaneous increase of labor productivity.

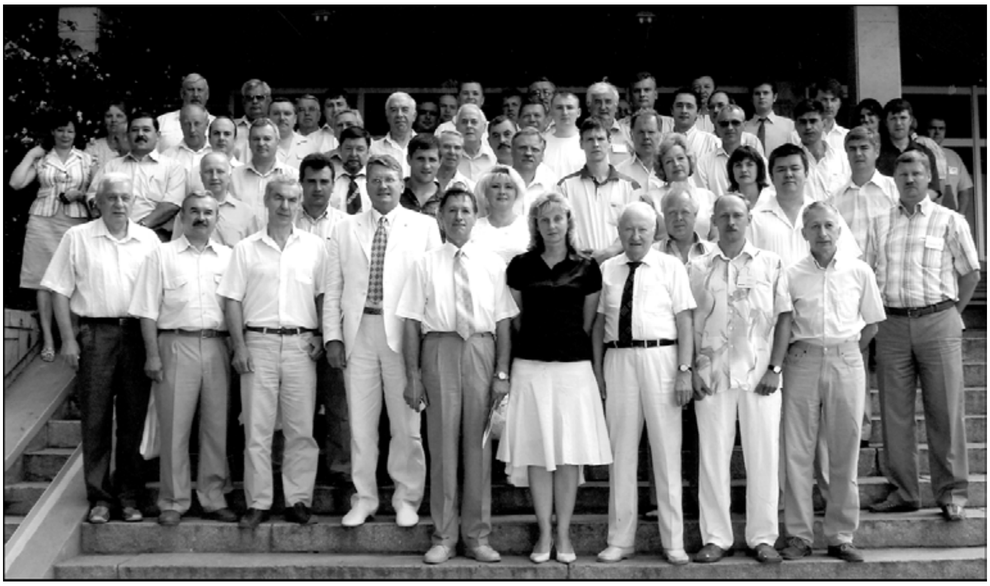
The association has accumulated experience in establishment of trade networks. Wide marketing service will continue to develop. The emphasis will be made on smooth transition to development of a network of representative offices of «Spetselektrod» and dealers in all regions of Russia and CIS. The rights of share holders of JSC «Spetselektrod» to their ownership were legalized. It means registration of the documents on privatization of the buildings and structures of all four enterprises and buying out of the land, on which they are located. This allowed quick capitalizing of the company property, due to which possibility appeared for crediting at dozens millions dollars. It is planned to emit shares for attraction of capital and further reconstruction of the enterprises. Growth of financial power and attraction of big financial investments are especially important during the period of entrance into WTO.

P.N. Pogrebnoj, manager of electrode production at «M.V. Frunze Sumy SPA» informed on energy conservation technologies, used at the enterprise in production of the coated electrodes. Traditionally high requirements are set at the association to the quality of welding materials, which is stipulated by the nomenclature of the produced equipment (for nuclear power plants, objects of oil and gas production, chemical industry, and main gas and oil pipelines).

Nowadays electrode production of the association represents a state-of-the-art module with closed technological cycle according to the classic scheme. Main units of equipment were supplied at the end of 1980s by Swiss company «Mansa Soudage». Similar equipment was, approximately, at the same time supplied by the same company to Volgodonsk, Izhora, Kazakhstan, and a little later to Sychyovka, Smolensk region. Because of sharp rise in price of energy carriers within the last two years it became necessary to deal seriously with their saving. First of all, for creation of the normal temperature conditions 80 % of exterior glassing were replaced for winterized «sandwich» panels, and overhaul of the remaining glassing was carried out. In addition, for creation of the necessary microclimate individual independent heating systems with temperature regulation within wide range were developed on the basis of serially produced in the association domestic gas boilers. These systems are used for thermostatting of liquid glass, heating of the electrode molding and drying premises, and thermo-constant warehouse of ready products. The chamber for preliminary drying (dry-curing) was developed by specialists of the association and built above chamber furnaces for heat treatment of the electrodes. The chamber has a perforated floor, which allows using heat from the calcination furnaces and thus saving energy resources. The chamber is equipped with an independent heating system, which acts around a year, and is additionally connected in winter to a central heating system. For removal of moisture from the chamber a specially developed ventilation system is mounted, which excludes formation of turbulent air flows.

For storage of the electrodes, designated for welding of special-purpose structures, a thermo-constant warehouse with independent and central heating systems, where the temperature not less than 25–30 °C and humidity not more than 50 % is constantly maintained, was built. Such conditions of storage in combination with reliable packaging ensure invariable quality of the electrodes within long term of their storage. Introduction of individual heating systems at the most responsible production bays, building of a thermo-constant warehouse for storage of electrodes and the dry-curing chamber, and wintering of the workshop building by the «sandwich» panels allowed reducing two-fold expenses for heating of the warehouse premises.

Technological conditions of boiling and refining of liquid glass were also reviewed. A silicate lump is carefully washed prior to being boiled soft, which allows subsequent reducing of energy consumption



during its filtration, and optimally selected conditions, in particular, steam pressure, time of boiling soft, and mass of a silicate lump and treated water loaded into the curing chamber, allow producing glass with preset parameters and significant saving of energy resources in the process of its refining.

Heat treatment is the main item of electric energy consumption in production of electrodes with the base coating. The enterprise uses chamber furnaces, supplied by the «Mansa Soudage» company together with main units of equipment for production of the electrodes. In addition to application of secondary heat for curing of the electrodes this equipment is peculiar for the following features: strict adjustment of operation of all zones of the furnace, including heaters and fans; optimal loading of the furnaces in regard to each diameter of the electrodes; optimal conditions of heat treatment.

For the purpose of saving of energy resources during calcination of the electrodes prior to their direct use, preservation of quality of the electrodes during their transportation and storage in a storage room with a respective climate, and convenience of application under erection conditions the technology was developed and vacuum packaging of the electrodes into special multibarrier films was introduced. Wide industrial tests of the electrodes in vacuum packaging, carried out within three months in acting workshops and during erection under climatic conditions of Tyumen, Kazakhstan, Turkmenistan and Iran brought positive results, whereby just expenses for a repeated calcination of the electrodes prior to their application exceed expenses on vacuum packaging. Testing in vacuum packaging of the electrodes, placed for two months into aquarium with water, showed that their humidity remained invariable.

So, introduction of listed measures allowed the electrode producer «M.V. Frunze Sumy SPA» reducing consumption of electric energy by 30, gas by 40 % and thermal energy two-fold, the production program remaining at the same level.

A.A. Chularis, doctor of technical sciences, professor of Donskoj STU, informed on peculiarities of certification and assessment of quality of the welding electrodes. In this field occur problems of organizational-methodological character. There are many problems of this kind, but the speaker dwelled upon the most apparent ones.

Complexities occur in certification of materials of different producers. This is stipulated by the fact that calcination of the electrodes is usually performed according to recommendations of the producers. But, if we analyze normative documentation of different objects, subordinated to «Rostekhnadzor», we will discover that one can not certify different producers under the same conditions, because if we speak about boiler-energy equipment — they have certain calcination terms and temperature-time conditions, while oil and gas producers have other conditions. Some departmental norms allow increasing a number of calcinations, which can cause strength reduction of the coating due to loosening of its surface. There is a need to develop a methodological approach. Consumers of welding materials should act in this field jointly with the producers. The optimum is necessary, which would really make it possible to objectively estimate this parameter.

As far as different thicknesses of the coatings are concerned, there is intention to ensure accuracy of measurements up to 0.01 mm, but a respective methodology is not available. Estimation of imported electrodes of different leading suppliers (KB Steel, Boehller, Tissen, ESAB, Lincoln) shows that after removal of the coating crock residual thickness of the coating on bars is quite different and it has a greater range. That's why development of more objective methodologies is needed with application of capacity or induction sensors.

Methodology of the coating strength estimation is outdated. When an electrode is lowered flatwise on a slab, one fails to avoid the effect of oblique collision in the area of transition to free end of the electrode (current lead). Electrodes of different diameters have different kinetic energy of collision. It is necessary to improve the methodology, taking into account the fact that an electrode with a coating is used in welding under static conditions.

As far as estimation of welding-technological properties is concerned, in the existing methodology, described in RD 03613 (2003), the estimation in points is used, which takes into account easiness of arc excitation, burning, etc. It is known that it is possible to excite arc by pecking and striking, while in the majority of the documents exactly striking is mentioned. And there is a reason for this, because real surface of an item is rough, and during striking a plurality of short circuits and a shorter period of transition to natural burning of the arc occur. A type of the power source is also important (alternative or direct current). For testing of the majority of rutile electrodes any type of the power source may be used, and for electrodes of the base type — usually a direct current power source. It is necessary to take into account open-circuit voltage of the power source, because the need to take into account the relation $U_a / U_{o.-c} = 1 / 1.8–1 / 2.5$ has its basis. Volt-ampere characteristic of the power source, intensity of the current increase after short circuit, and inductiveness of the welding circuit should also be taken into account. That's why clear methodological instructions in respect to specific limits of the power source parameters in performance of the tests of welding-technological properties of the electrodes are necessary.

There is also uncertainty in relation to consideration of the hydrogen content. One can not find anywhere the requirements that would specify, which electrode materials should be tested for determining content of hydrogen in the deposited metal.

In the conference debates participated doctor of technical sciences V.N. Shlepakov, candidate of technical sciences I.R. Yavdoshchin (E.O. Paton EWI), N.N. Makhrushan (Administration of Krasnodar region), doctor of technical sciences A.A. Chularis (Donskoj STU), P.I. Moiseenko (Oryol plant of «Severstal-Metiz»), V.G. Lozovoj, V.M. Dzyuba (STC «Welding Consumables»). In their opinion the conference was a success due to its business-like efficiency, constructive character, and adherence to reality. At the same time a number of wishes for future work of the association were voiced. It is desirable to structure the reports, to be presented at the conference, by separate problems. In addition, if they are available on hard copies, they have to be presented at the conference in a thesis form, which will allow allocating more time to discussions of main results. The association has to look for such principles of preparation and conducting of the conference, which would ensure frank exchange of the information for development of new technological solutions. It is important for the association to actively participate in perfection of the normative-technological base in the field of welding materials and certification thereof. The association has accumulated positive experience of work and there is a need to establish its own website for operative placement of the materials concerning current technical and organizational issues in different fields. It would be also useful to organize publishing of the information leaflet with, for example, following sections: raw materials — equipment — new developments of materials.

The participants noted with satisfaction usefulness of the held exchange of opinions on the problems included into the reports, and approved of big work fulfilled by former president of the association (A.I. Bugaj), executive director of the association (P.V. Ignatchenko), director-general (V.M. Dzyuba), deputy director (V.G. Lozovoj), and chief accountant (O.M. Dzyuba, Yu.M. Borieva) of SPC «Welding Consumables» in organization and conductance of the conference and publication of the collection of reports. Significant contribution of the association into development of production of welding materials in CIS countries and development and provision of production lines with technological equipment, introduction of new technological processes, and certification of the products, quality control systems, and technical regulations were emphasized. All this positively effected state of welding production in CIS countries. Importance and usefulness of presented at the conference reports, which were recommended to the producers of welding materials for practical application in their everyday activity, were noted. The «Elektrod» association plans development in near future of new competitive welding materials, corresponding to the level of leading foreign countries, which will be developed in two ways: individually by own forces with attraction of extraneous organizations or jointly by two-three enterprises-manufacturers of welding materials. The most important direction of activity of the enterprises-manufacturers of welding materials is bringing of the quality of produced by them materials up to the level, corresponding to WTO requirements.

ARGON-ARC WELDING OF BILLETS OF SHAFTS FOR METALLURGICAL EQUIPMENT

V.M. KULIK, M.M. SAVITSKY, A.F. LUPAN, L.A. CHERTORYLSKY and **V.E. SUKHOYARSKY**
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Peculiarities of argon-arc tungsten-electrode welding of shaft billets are considered. Application of an activating flux (A-TIG) welding makes it possible to decrease the depth of the weld groove, which is them filled up with filler metal during the TIG process. It is shown that thermal cycling and auto-heating in multilayer welding lead to decrease in the cooling rate, formation of more equilibrium structures, and prevention of cold cracking. In as-welded condition the joint metal has increased hardness and microhardness compared to base metal, and after comprehensive heat treatment the welded joint has the properties close to those of the base metal.

K e y w o r d s : argon-arc welding, shaft billets, low-alloyed steels, circumferential butt joint, penetration, weld, HAZ, cooling rate, structure, joint properties

Heat-hardened spline and articulated shafts of 150–320 mm diameter and 1–2 m length with end parts thickened 1.5 and 2.5 times are used in metallurgical equipment. Local increase of the diameter leads to considerable metal losses in chips in manufacture of shafts, increased power and labour consumption. Improvement of the performance of such shafts is achieved by lowering their weight by making them hollow, welding the shaft parts of different diameter from different steels (Figure 1) and heat-hardening. Sections exposed to contact wear are subjected to case-hardening. In order to reduce the punching of the case-hardened layer at high specific loads, it is rational to increase its thickness, strength and hardness of steel. Light-weight shafts are made of alloyed 20Kh and 18KhGT steels, in which the presence of chromium and manganese promotes an increase of the case-hardened layer thickness, an essential reduction of case-hardening time and power consumption [1], and titanium presence inhibits the austenite grains growth. Considering the cost and other factors replacement of steel 20Kh by carbon steel 20 is allowed for the less loaded parts.

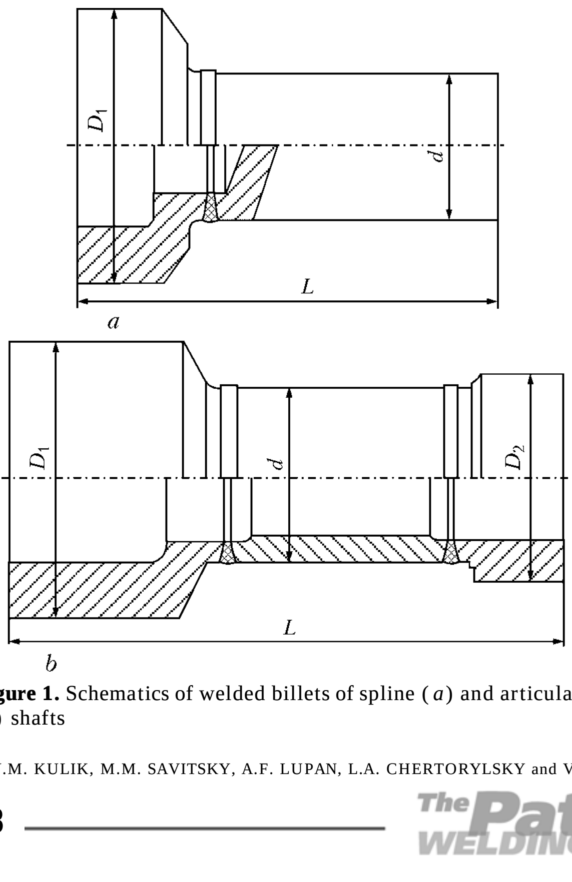

Figure 1. Schematics of welded billets of spline (*a*) and articulated (*b*) shafts

The used 20Kh and 18KhGT steels with the carbon equivalent of 0.40–0.57 and 0.50–0.67, respectively, are potentially prone to cold cracking in welding (unlike steel 20 with C_{eq} = (0.23–0.35 %) < 0.45 %. Application of preheating and postweld heat treatment of the product usually prevents cracking, but makes the technological process more complicated. Use of high-alloyed welding consumables for heat-hardenable shafts is unacceptable, because of development of structural-mechanical inhomogeneity in the zone of fusion of dissimilar steels and an abrupt lowering of operational reliability of the welded joint.

Performance of auto-heating and self-tempering in multilayer welding of a circumferential joint is more justified. Auto-heating and concurrent heat treatment of hardening steels are implemented in the technologies of welding electric drill cases with the wall thickness of 22 mm and reconditioning of massive rotors by cladding without application of preheating and post-weld heat treatment [2, 3].

Presence of increased stress concentrations, residual stresses and non-uniformity of mechanical properties leads to lowering of fatigue life of steel welded joints compared to base metal [4]. The lowest stress concentrations are found in butt joints made by non-consumable electrode argon-arc welding. Increase of cyclic crack resistance of high-strength steel welds up to base metal values is also achieved by quenching and tempering [5].

The purpose of this study is development of the technology of butt welding of billets of shafts, designed for operation in metallurgical production.

Optimizing the technology and modes of multilayer tungsten-electrode argon-arc welding of billets

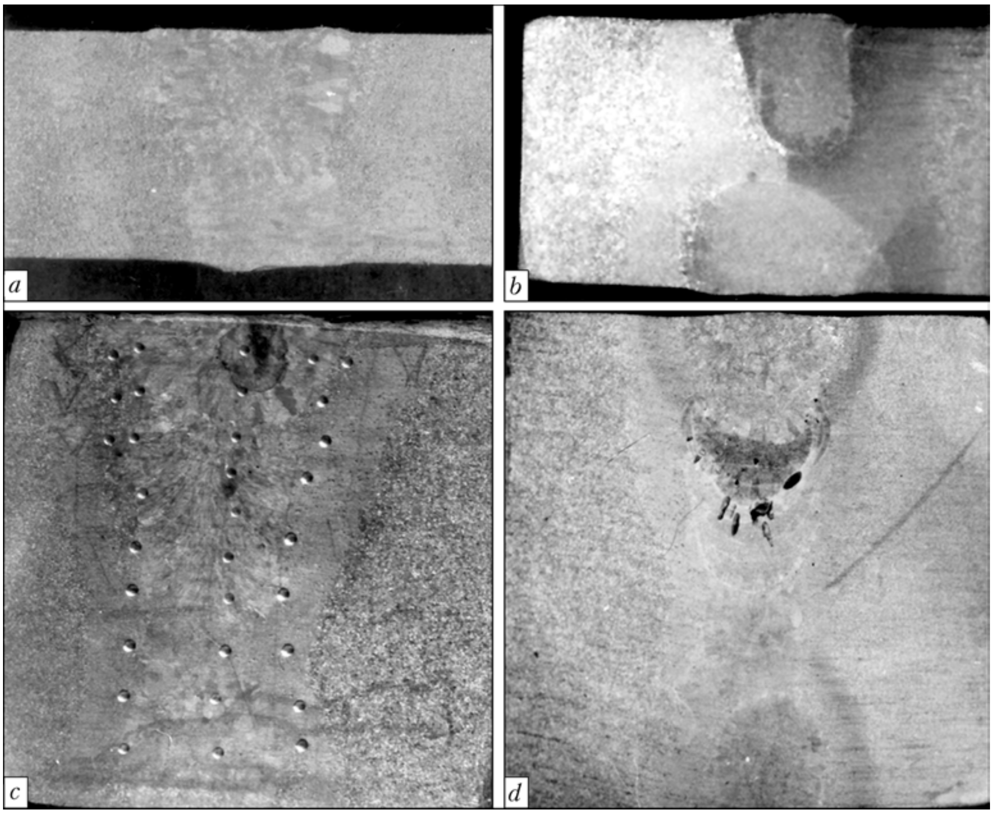

Figure 2. Macrosections of circumferential joints 14 (*a*) and 18 (*b*) thick without edge preparation, and 33 mm thick (*c*, *d*) with edge preparation: *d* — with pores in the weld with filler metal of 08MD type

of shafts of different typesizes was performed on hollow cylindrical samples with outer diameter of 108–192 mm with wall thickness of 14, 18 and 33 mm. Welding on the outside and inside was performed with deep penetration in the first passes on each side after deposition of activating flux VS-2E on the surface (A-TIG welding) [6, 7], which allows reducing the depth of edge preparation, number of welding passes, consumption of welding consumable and power. At subsequent passes without the activating flux application (TIG welding) the outer U-shaped groove is filled with filler metal (Sv-10G2M, Sv-10Kh2MD, Sv-08Kh3G2M, Sv-20Kh4GMA, Sv-08MD welding wire). The latter were selected allowing for the increase of the weld fatigue threshold at lowering of carbon content from 0.30 to 0.15 % [5]. In welding ARK-1 machine, VSVU-315 and VDU-504 rectifiers and OB-631 manipulator were used as a system.

Part of welded samples were subjected to high-temperature heating, water quenching and low-temperature tempering (both at chemico-thermal and heat treatment of the shafts). Composition, macro- and microstructure, distribution of *HRB*, *HRC* hardness and microhardness were studied, and joint strength was evaluated. Ultrasonic testing of circumferential butt joints of shaft billets was performed.

In A-TIG welding of circumferential samples 14, 18 and 33 mm thick the maximum penetration depth is equal to 11, 10 and 8 mm, respectively. In the first case in welding from both sides without edge preparation, weld continuity across the entire thickness is ensured (Figure 2, *a*), and in the second and third — lacks-of-penetration in the joint middle (particularly at penetration shifting off the butt), and an abrupt lowering of its cyclic fatigue life (Figure 2, *b*) are found. Overlapping of penetration in A-TIG welding and continuity of such joints across the entire thickness are ensured as a result of edge preparation to the depth of 2–3 and 19–21 mm, respectively, with the toe of 15–16 and 12–14 mm and groove filling with filler metal at subsequent TIG welding passes (Figure 2, *c*).

Deep penetration in A-TIG welding with the form factor of 1.0–1.5 leads to formation of columnar oriented towards the center, and disoriented refined crystallites in the center in the weld metal. In the section formed by TIG welding with filler metal melting, a vertical component of crystallite orientation from the earlier deposited layer is found. In a multilayer weld the crystallites are growing from the base metal in the form of spatial curved bodies, bending upwards with prevalence of the vertical component in the weld central part. In the butt joint a HAZ of up to 3–5 mm width is visually detected, which increases from the first penetrations in A-TIG welding towards the butt outer surface.

Composition of weld metal in A-TIG welding is an intermediate one between the steels being welded and varies within the range of their grade composition, while the metal composition in TIG welding is close to filler wires, in particular in their simultaneous addition to the welding zone (Table 1). Carbon content in the weld can decrease 1.3–2 times, while the change of the wire grade during welding involves the respec-

Table 1. Composition of weld metal produced with and without filler wires

#	Steels of circumferential butt joint	Filler metal	Element weight fraction, %				
			Ñ	Si	Mn	Cr	Mo
1	20 + 20Kh	–	0.18	0.27	0.71	0.71	< 0.03
2	20Kh + 18KhGT	–	0.080–0.012	0.29–0.33	0.60–0.77	0.98–1.20	–
3*		–	0.18	0.26	0.76	1.08	< 0.03
4		10G2M	0.08	0.18	1.26	0.78	0.05
5		08Kh3G2M	0.06	0.44	1.43	1.60	0.16
6*		10Kh2MD	0.07	0.37	1.92	0.98	0.07
7		20Kh4GM	0.24	0.32	0.68	1.70	0.15
8		10G2M + 20Kh4GM	0.09	0.11	1.05	0.57	0.05
9*		08Kh3G2M + 20Kh4GM	0.08	0.46	1.36	1.73	0.18

*Base metal partially penetrates into the spectral analysis zone.

tive change of the metal composition in the next layer and controlled differentiation of hardness along the weld height (Table 2). Pores can form in the weld produced with melting of Sv-08MD wire containing a small amount of deoxidizers (Figure 2, *d*).

The cooling rate in welding, which determines formation of the joint metal structure calculated by the plane layer schematic [8], when temperature distribution across the thickness is non-uniform, was determined by the following formula:

$$W = \omega 2\pi\lambda \frac{(T - T_0)^2}{q / v}, \qquad (1)$$

where $\lambda = 0.38$ W / (cm·deg) is the coefficient of steel heat conductivity; T_0, T are the initial and current temperatures at metal cooling, respectively; q is the heat input; v is the welding speed.

The parameter depends on the dimensionless criterion

$$\frac{1}{\theta} = \frac{2q / v}{\pi\delta^2 c\rho(T - T_0)}, \qquad (2)$$

where δ is the butt thickness; $c\rho = 4.8$ J / (cm^3·deg) is the steel heat capacity.

At temperatures of low stability of austenite of 500–600 °C the cooling rate $w_{6/5}$ of a joint of 14–33 mm thickness in the first pass of welding with $q / v = 24290–25846$ J / cm can be 5.5–25.2 °C / s, increase of butt thickness within the above limits causes 4.6 times increase of $w_{6/5}$. Auto-heating during welding up to 100 and 200 °C, contrarily, leads to lowering of the cooling rate by 1.43–1.65 and 2.52–3.91 times, respectively.

According to the diagrams of over-cooled austenite decomposition [9] the diffusion, intermediate as well as diffusionless transformations occur at welding rates of cooling of steels 20, 20Kh and 18KhGT. Repeated heat impacts in multilayer welding causing an overall temperature increase and lowering of the rate of subsequent cooling, promote a reduction of the amount of the forming martensite (right up to prevention of its formation) in the structure, an essential increase of the duration of self-tempering of the initially and re-hardened metal [10, 11]. Thermal cycling with heating above A_{c3} refines the austenite grain, heating below A_{c3} ensures tempering of the hardened metal. This results in formation of different combinations of structural components (ferrite, pearlite, bainite, martensite) in joints of different steel grades, thicknesses in different sections, in particular, in the HAZ metal (Figure 3). In steel 20Kh no martensite is detectable, and in 18KhGT steel its content visually is much lower than the critical value $M_{cr} \geq 50–70$ % for alloyed steels with 0.15–0.30 % C [10, 12]. This in combination with refinement of the austenite grain and concurrent tempering prevents the delayed fracture susceptibility or cold cracking in welded joints.

HAZ metal of 18 mm thick joint on steel 20 has the microhardness *HV*0.2-130–180, that of steel 20Kh is *HV*0.2-160–190 and of steel 18KhGT is *HV*0.2-165–200. Lower microhardness values are found in sections which are the last to form, where a more equilibrium structure forms due to a lowering of the cooling rate. Sections of welds on steels 20 + 20Kh and 20Kh + 18KhGT formed without the filler material have the microhardness *HV*0.2-125–185. It is lower in the first layer, particularly, from the side of the third layer, where the metal heated above A_{c3} is cooling slowly. An increased alloying of filler metal promotes an increase of weld microhardness up to *HV*0.2-200 and *HV*0.2-200–230 when Sv-10Kh2MD and Sv-20Kh4GMA wires are used. Higher microhardness *HV*0.2-210–310 and *HV*0.2-305–375 of welds of steels 20Kh + 18GKhT in sections formed without and with 08Kh3G2M filler metal, respectively, is observed in a butt joint 33 mm thick cooling at a high rate.

Weld and overheated zones of HAZ metal have Rockwell hardness higher than that of base metal, which is usually higher in the weld than in the metal of the HAZ of at least one of the welded steels (Table 2). It varies both along the height and across the joint and depends on the thickness of the butt joint, sequence of layer deposition, composition of the metal being studied. Higher hardness and strength, respectively, lead to fracture of the tested welded samples

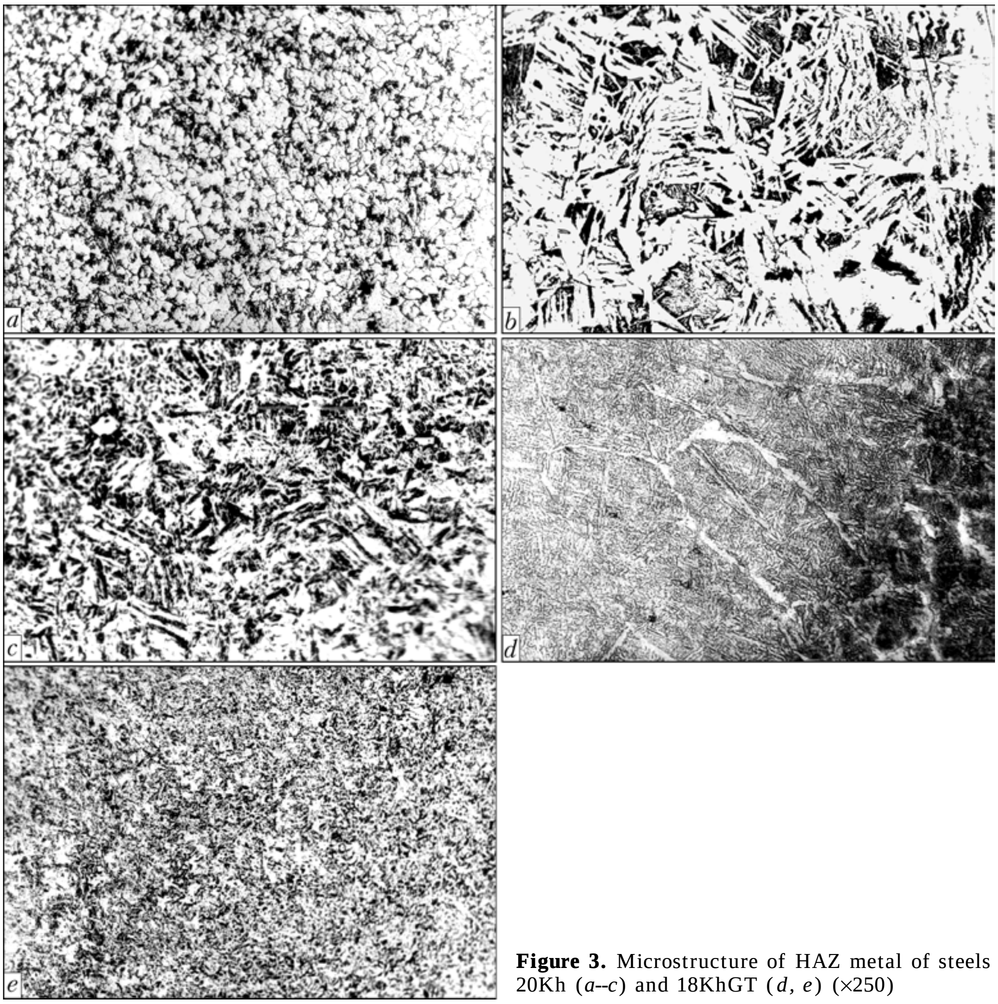

Figure 3. Microstructure of HAZ metal of steels 20Kh (*a*--*c*) and 18KhGT (*d, e*) (×250)

of 20Kh + 18KhGT steel of different alloying across the lower alloyed steel 20Kh at σ_t = 603.5–605.1 MPa.

After heat treatment including simulation of case-hardening conditions, hardening and low tempering, steel 20Kh and its HAZ metal acquire hardness *HRC* 34–46, 18KhGT steel and its HAZ metal — *HRC* 41.5–47.0, respectively. Hardness of weld section formed by melting of steels without filler metal, increases up to *HRC* 36–45 and becomes an intermediate one relative to steels being welded. Weld metal of 10G2M type acquires hardness *HRC* 33.5–40.0, 10Kh2MD — *HRC* 41–46, 08Kh3G2M — *HRC* 33.5–40.0 respectively. Comprehensive heat treatment ensures refinement of metal structure, overall strengthening of the welded item and achieving close values of welded joint properties compared to the base metal. Welded samples of the inner (without filler metal) and outer (with filler metal) parts of the circumferential butt joint after hardening and low-temperature tempering have σ_t = 1356.7–1369.6 MPa and fail in the base metal at testing. Similar samples also subjected to pre-normalizing and heating, simulating the case-hardening conditions, have σ_t = = 1104.0–1255.1 MPa and may fail at testing both in the base metal and in the weld.

Technologies of argon-arc welding without post-weld tempering of hollow and partially hollow cylindrical billets of shafts (Figure 4) have been developed, taking into account the investigation results. Depending on the shaft billet typesizes, modes and features of multilayer welding, cooling of the joints after welding to 100 °C occurs during one-four hours without cold cracking. Plane and three-dimensional, extended and short internal defects in circumferential joints of the billets are not detected by ultrasonic testing. The developed technologies were used to manufacture four

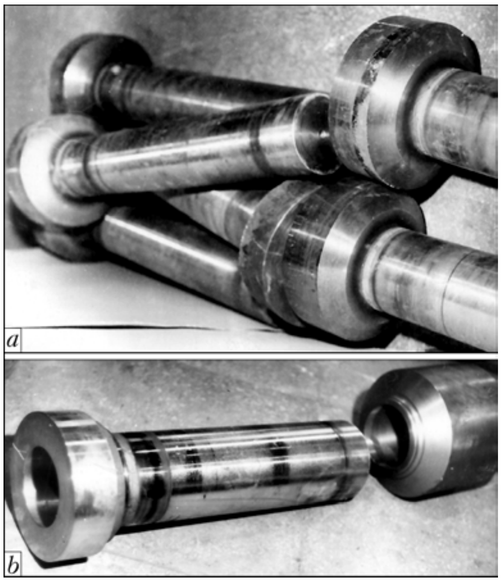

Figure 4. Welded billets of spline (*a*) and articulated (*b*) shafts

Table 2. Metal hardness in joints of different thicknesses and grades of steels made with different filler metals

#	Steels welded		Layer #	Filler metal	Hardness *HRB* (*HRC*)		
	Grade	Thickness, mm			HAZ	Weld	HAZ
1	20 + 20Kh	14	1 2 3	– 10G2M –	– – –	92–94 83–84 95–97	91–94 94 88–90
2		14	1 2 3	– – 10G2M	– – –	90–95 94–95 84–89	90–93 88–93 81–84
3	20Kh + 18KhGT	18	1 2 3	– 20Kh4GM –	97–99 – (23–24)	97–98 (36) (25.5–26.0)	– (21–22) (25)
4		18	1 2 3	– – 20Kh4GM	97–98 (22.5–24.5) (20.5–22.0)	97 (23–26) (35.0–35.5)	98–99 97–100 98–102
5		18	1 2 3, 4	– – 20Kh4GM	94–98 97–98 99–101	98–99 (24.0–24.5) (35–38)	94 98–99 99
6	20Kh + 18KhGT	33	1 2 3, 4 5–7	– – 08MD 10Kh2MD	(23) (20) 88–90 90–98	(25.5) (23.5) 86–88 (26.5)	(24.5) (20.5) 89–93 (24.0–25.5)
7		33	1 2 3–6	– – 10G2M	91 85 87–98	98 89 85–93	95 90 86–100
8		33	1 2 3–6	– – 08Kh3G2M	88–90 85–87 90–101	98 99 99–102	97 89–92 90–102
9		33	1 2 3–6	– – 10G2M + 20Kh4GM	85 90 85–95	95 95 91–95	94 100 94–100
10		33	1 2 3–6	– – 08Kh3G2M + 20Kh4GM	86 90 86–91	(26) (26) (26–27)	92 101 92–101

Note. Steel 20 — as-delivered, *HRB* 84–86; steel 20Kh — *HRB* 88–90; steel 18KhGT — *HRB* 89–90.

Table 3. Overall dimensions of welded shaft billets

#	Shaft type	D_1	D_2	d_3	L
1	Articulated	250	205	108	1410
2	Spline	250	–	160	1150
3	Articulated	320	250	192	1045
4	Spline	320	–	166	1016

industrial batches of spline and articulated shafts with application of normalizing, case-hardening, hardening and tempering (Table 3).

In conclusion it should be noted that manufacture of shafts using a rational kind of rolled stock (pipes), combination of round billets of different diameters using welding technology, and elimination of post-weld furnace tempering from the technological process ensure an essential lowering of the consumption of power, metal and labour. Light-weight shafts promote improvement of operating characteristics of metallurgical equipment.

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METHODS OF RECONDITIONING ROTARY KILNS (Review)

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The causes for failure of the bands of rotary kilns in operation are analyzed. The existing methods of repair of the through-thickness cracks in the bands without their dismantling from the kiln body are considered. Comparative analysis of the effectiveness of repair operations with application of arc and electroslag welding is given.

Keywords: rotary kilns, bands, cracks, repair methods, mounting conditions, electric arc welding, automatic welding, electroslag welding, multilayer electroslag welding

The main elements of process lines for cement production, kilning of raw materials in the metallurgical, chemical and other industries, are such metal-intensive large-sized units, as rotary kilns of 3.7--7.0 m diameter and 75–230 m length (Figure 1) [1]. In the kilns operating in the continuous mode, high-temperature treatment of raw materials is performed to produce cement clinker, lime, plaster, alumina, metallurgical pellets, etc. Depending on the type-size, the rated hourly efficiency, for instance, of cement kilns, is equal to 22--125 t of clinker. Therefore, emergency stoppage of a kiln of 5 m dia × 185 m leads to factory losses (just because of underproduction) of up to 75 t of klinker per every hour of downtime.

The rotary kiln body [1] is a relatively thin-walled (S = 16–30 mm) cylindrical shell with thickened underband shells (S = 40--100 mm), loaded along the length by forces from the kiln own weight, weight of lining and weight of processed material, and at the same time loaded by concentrated forces acting in the contact areas between the body and bands. Concentrated forces induce the highest stresses in the body and components of the kiln in the support area. Depending on the kiln length from four to nine support bands are mounted on its body. In kilns of 5 m and greater diameter a support reaction reaching 4000 kN and more is transferred to the body (in the points of band mounting) [2].

The most heavy-duty and critical parts of rotary kilns are support bands of a solid rectangular cross-section put on the kiln body with a certain radial gap, as well as solid bands of a shaped cross-section welded into the kiln body [3].

For kilns of more than 4.5 m diameter outsize bands are widely used, which are made of two finished cast halves by electroslag welding (ESW) in the site of kiln mounting [4]. Most of the bands are made from medium-carbon steels 35L, 30GSL and 34L-ESh. Cross-sectional dimensions of cast-weld bands are (355–500) × (900–1350) mm.

Extensive experience has been accumulated so far of manufacturing cast-weld bands under production and site conditions from steels 30L, 35L, 25GSL and 30GSL. The technology of assembly and welding of finished band halves to ensure accurate dimensions is optimum [5]. Both the band butt joints are welded simultaneously by ESW, which is followed by local heat treatment of welds using portable electric furnaces.

Total service life of the bands should be not less than 21 years at 0.6--2.0 rpm, and not less than 19 years at 2.1–3.5 rpm [2]. However, in practice not all the bands operate through the specified operating life because of fracture in the cross-section, excess wear and chipping of metal on the rolling surface, etc.

Many years of practical work showed that the main cause for prolonged downtime of the above process lines is formation of through-thickness transverse cracks in the rotary kiln bands (Figure 2).

Figure 1. Rotary kilns of 5 m dia × 185 m with bands of a rectangular cross-section mounted on the kiln body with a radial gap (a) and welded-in shaped bands (b)

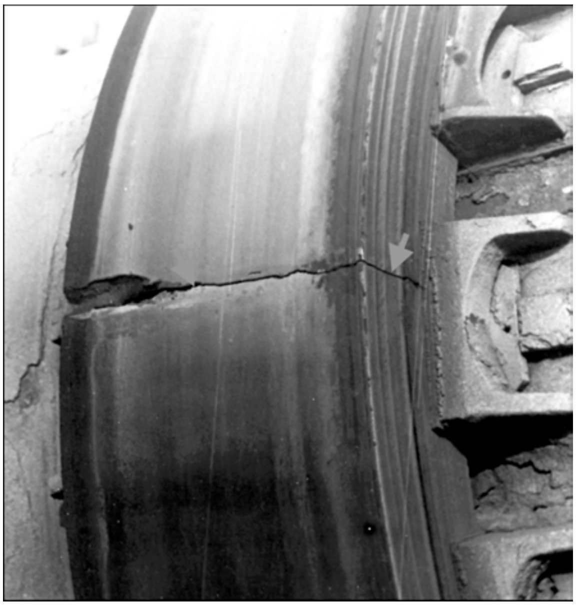


Figure 2. Typical fracture of a band of the rotary kiln as a result of the formed transverse crack

Considering that there are more than 100 cement works in CIS countries, in each of which two and more continuous production lines are in operation, more than 1200 cast-weld bands are continuously operating in the rotary kilns. According to the survey data of the reliability bureau of CJSC «Volgotsemmash» which for forty years has been the head enterprise on rotary kiln manufacturing, in total from three to seven bands fail every year because of cracking just in the cement industry, with through-thickness cracks forming in 86 % of the cases [6].

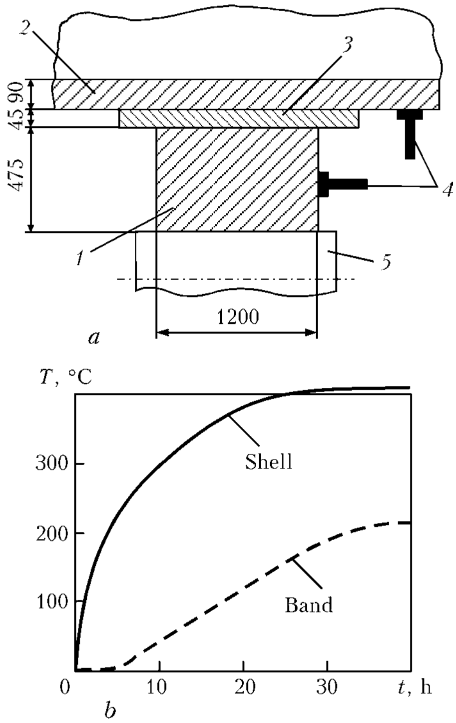


Figure 3. Schematic of location of temperature sensors (*a*) and plot of heating (*b*) of the band and underband shell of the hot end of the rotary kiln of 6.4 / 7.0 m dia× 95 m in the start-up period: *1* — band; *2, 3* — under band shell and cover plate, respectively; *4* — thermometers; *5* — underband roller

The conducted statistical analysis showed that most of band failures were observed in cement works fitted with the largest kilns 95 m long and 6.4 / 7.0 m in diameter (about 70 %) for the dry method of cement production. A characteristic feature of these kilns operation is accelerated heating of the hot zone in the start-up period, which results in a large difference in the heating temperatures of the underband shell and the band. At the initial moment (6 h) heating of the underband shell (230 °C) and increase of its diameter result in liquidation of the specified radial (thermal) gap (from 7.5 up to 0 mm) between the band and the shell (Figure 3). This is the moment of the start of the condition of band expansion by forces induced by temperature stresses in the underband shell and presence of inherent stresses in the band from temperature gradient across its thickness. The second factor influencing the band load-carrying capacity, are transverse bending deformations from the roller support reactions and conditions of redistribution of mechanical loads in the kiln supports owing to distortion of its geometrical form during operation (Figure 4).

Indirect assessment of band bending deformations is performed by measurement of transverse deformations of the kiln body in the area of band mounting. For this purpose a portable mechanical instrument (D9-A deformation recording instrument) with magnetic attachment is mounted on the kiln body [7], which incorporates an automatic recorder allowing obtaining in 100:1 scale the geometrically similar patterns of body deformations during the kiln rotation (Figure 5, *a*).

Deformations are recorded in the cross-sections of the body located at the distance of half of the kiln body diameter on both sides from the band middle section [7]. In each cross-section the deformations are recorded in three points located equidistantly on the outer circumference of the kiln body. The points of

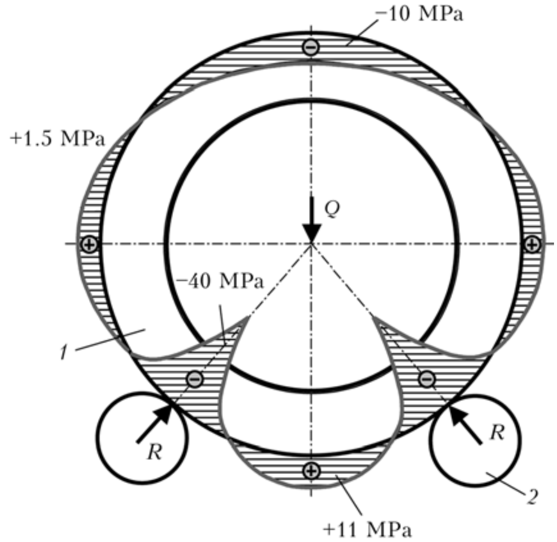


Figure 4. Epure of stresses in the outer band layers of the rotary kiln from roller support reactions (without allowing for the rolling moment): *1* — band; *2* — support roller (Q = 7.2 MN; R = = 4.16 MN)

measurements in different cross-sections are located on the same generatrix of the kiln body (see Figure 5).

Measurements of transverse deformations of kiln bodies of 5 m and greater diameter showed that the highest overloads of the supports exceeding the average values more than 1.5 times and leading to considerable bending stresses in the bands mounted on the underband shell with a radial gap, develop in the second supports from the cold end and the ones before the last at the hot end [7].

Measurements of the kiln body rectilinearity revealed considerable distortions of its longitudinal axis, this leading to a non-uniform distribution of the loads in the supports [8]. It is established that the overloads of the supports resulting from the local distortion of the kiln geometrical axis during its operation are 2–3 times higher than the design load.

It is obvious that superposition of the support overloads and exceeding the admissible sagging may lead to crack development, which further on may lead to a complete failure of the band. Analysis of band failure showed that accidents occur the most frequently exactly on supports second from the edge, as well as the ones next to them [7, 9]. Measurements (with participation of one of the authors of this paper) of transverse deformations of the kiln body of 5 m dia × 185 m at PA «Novorostsement», in which ESW bands were welded-in in the hot zone, showed that this type of deformations are practically absent, which is attributable to an essential increase of the body rigidity in the support area. Mounting welded-in bands allowed a significant increase of the kiln lining resistance. However, such a band design creates a section with a high moment of inertia, which is unfavourable for the span shell performance. Increased rigidity of the kiln body in the area of welded-in band mounting and errors of roller support mounting also often lead to support overloads (tearing of the band rolling surface from the roller supports is observed), and this results in failure of welded-in bands. Cracks initiate in the shells to which the band is welded, and then damage the band bulk.

Thus, out of all the diversity of factors adversely affecting the load-carrying capacity of the rotary kiln bands, the following can be singled out as the main ones (Figure 6):

• non-uniform temperature loads as a result of fast heating of the body in the start-up period in rotary kilns of more than 5 m diameter and liquidation of the radial (thermal) gap between the band and the underband shell;

• non-uniform distribution of mechanical loads on the supports of rotary kilns of 5 m and greater diameter inducing high bending stresses;

• weakening of the band cross-section as a result of the presence of hidden metallurgical defects in the casting and welded joint defects such as non-uniformity of mechanical properties, shrinkage cavities, flokens, tubular pores, lacks-of-penetration, cracks in the weld, etc.

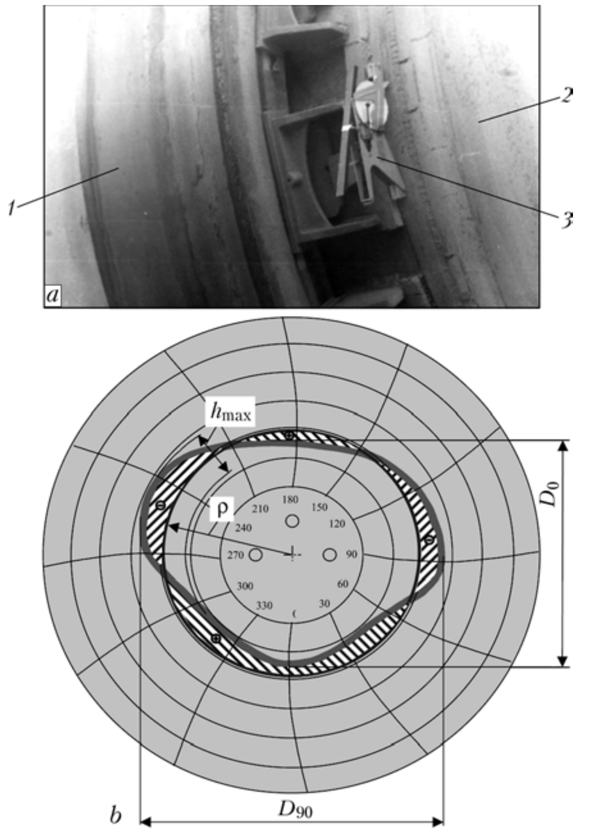


Figure 5. Fragment of conducting strain measurement (*a*) and illustration of the strain diagram (*b*) of the actual condition of sagging of underband shell of a rotary kiln of 5.6 / 5.0 m dia × × 185 m: *1* — band; *2* — underband shell; *3* — strain meter D-9A; h_{max} — difference of maximum sagging; D_0 and D_{90} — vertical and horizontal dimensions of the strain diagram (recording scale 100:1), mm; ρ — radius of neutral circumference, mm

Influence of the first factor is reduced by improvement of the technology of kilning unit operation, that of the second — by changing the design of the kiln support assembly (for instance, by mounting the roller supports on pneumocushions of PWI design) [9], that of the third factor — by improvement of the quality of billet casting, technology of their welding, heat treatment and improvement of the methods of quality control in band manufacture.

However, the issue of conducting repair operations of failing equipment in the site of its operation is still urgent.

Repair of such large-sized parts as bands of rotary kilns, is practically impossible without welding ap-

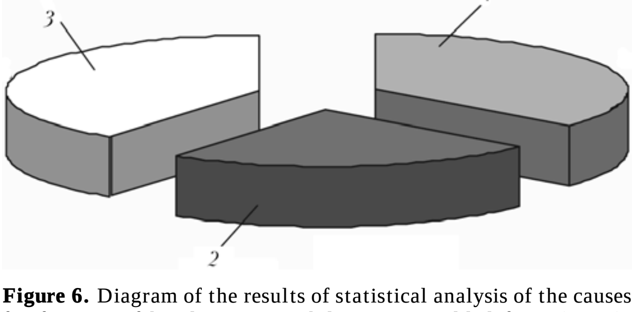
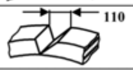
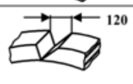
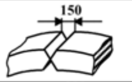
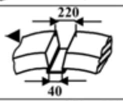
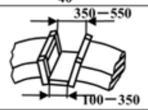
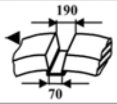
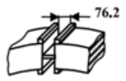
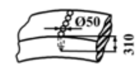
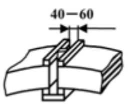


Figure 6. Diagram of the results of statistical analysis of the causes for fracture of bands in rotary kilns: *1* — weld defects (36 %); *2* — casting defects in band manufacture (24 %); *3* — violation of the kiln operation rules (40 %)

Methods of repair of cracks in bands without their dismantling from the rotary kiln body

No.	Enterprise, rotary kiln dimensions	Crack location	Welded section, mm	Groove shape	Volume of edge preparation, cm^3	Method of crack welding up	Machine welding time, h	Deposited metal weight, kg	Method of preheating and heat treatment	Total repair time, h
1	PA «Volsktsement», Ø5×185 m	Weld	–	Replacement of a defective band by a new one by dismantling the band block from the kiln body						276–1440
2	PA «Mordovtsement», Ø5.6/5.0×185 m	Base metal	1000×400		26000	Coated-lectrode manual arc welding	105	225	Gas torches	290
3	PA «Akmyantsement», Ø5×185 m	Welded joint	1000×400		22000	Same	91	172	Coke oven	170
4	Topkinsky Cement Plant, Ø5×185 m	HAZ	1000×400		24000	Mechanized flux-cored wire welding	76	187	Same	126
5	Serebryakovsky Cement Plant, Ø5×185 m	Weld	1000×400		30000	Same	106	270	Gas torches	291
6	OJSC «Poltava GOK», Ø6×60 m	Base metal, welded joint	1118×500		72670	Automatic submerged-arc welding	288	567	Same	384
7	Achinsky Alumina Works, Ø5×185 m	Same	1000×450		101250–202500	Automatic twin-wire submerged-arc welding	183–367	790–1580	Put-on electric furnace	255–440
8	Navoi Cement Plant, Ø6.4/7.0×95 m	Welded joint	1200×475		75600	Automatic submerged-arc welding	240	650	Same	864
9	«Tilden Mining Co.», USA, Ø7.5×48 m	Weld	1016×508		38400	Same	336	306	»	504
10	PA «Bryansktsement», Ø5×185 m	Base metal	1000×310		12170	Multilayer ESW of blind holes	16	95	Gas torches	72
11	Novo-Spassky Cement Plant, Ø6.4/7.0×95 m, Ulianovsky Cement Plant, Ø5.0/5.6×170 m	Weld, base metal	1200×475 1000×450		31350 25030	Single-pass consumable-nozzle ESW	4 2.5	245 196	Put-on electric furnace	96 96

plication. Restoration work using welding processes has always been urgent at liquation of accidents in the continuous production lines. Two variants of liquidation of the consequences of band failure are known and are applied in practice:

• replacement of a failing band with the new one [10];

• repair of a crack in the band directly on the kiln body by different processes of fusion welding (Table) [11].

Work performance by the first variant includes cutting the kiln body, removing the band with underband shell, and in a number of cases also removal of two adjacent shells, mounting a new underband shell with a new band and its welding to the kiln body [10]. These measures are preceded by work on removal of the refractory lining of the kiln and its subsequent restoration. Depending on the readiness and organization of the work such repair can take from 12 to 60 days and is the most labour-consuming and expensive (Table, item 1).

Also know is the method of replacement of worn bands, eliminating the cutting up of the kiln body [12]. In one of the USA cement-making plants the worn bands of the rotary kilns were replaced by new ones made of two halves. The defective band was cut in the horizontal plane into two parts and the halves were dismantled. Two halves of the new band were successively put on the underband shell, and they were temporarily connected by a locking ring. Then both halves of the band were connected by tie bolts. After replacement of the locking ring the tie bolts were replaced by steel rods, which were welded from the inside and outside. The locking rings were welded to underband plates. The entire operation of replacement of a worn band by the new one took two days. Such a repair technology is applicable for small diameter kilns, where bands of an open section are used. However, practical application of bands of such a design is not known either in Ukraine, or in Russia.

In most of the cases crack repair is performed by the second variant, i.e. welding up of cracks is performed without removing the band from the kiln body.

For this purpose the band is moved so that the failure area were strictly in the upper position by rotating the kiln body. In order to place the welding equipment on the kiln body, a platform with a timber flooring and canvas cover is mounted and a two-flight stairway is made.

Cracks in the band are most often repaired using coated-electrode manual electric arc welding [13]. In such cases crack cutting out is performed by flame cutting, making a V- or X-shaped groove (Table, items 2, 3). To ensure weld root penetration, copper backing plates of 8 mm thickness are used. Welding is performed by the known «hill» method from the butt middle to the band edges. Weld formation along the groove edges is free. Two welders perform welding continuously and simultaneously with peening of each weld layer. Electrodes of UONI-13 / 55 grade of 5 mm diameter are used for welding. Total duration of repair of a through-thickness crack in the band of a rotary kiln of 5 m dia $\times$ 185 m with manual welding application is 7–12 days.

Known is the experience of welding up cracks in the bands with application of flux-cored wire mechanized arc welding (Table 2, items 4, 5). The root pass is made by manual arc welding. When X-shaped groove is used, it becomes necessary to cut out windows in the underband shell, which is performed after dismantling the lining. Welding is performed similar to the previous case, two welders working simultaneously, but in two stages. First the groove outer part is welded (from the side of the band rolling surface), then the kiln body is rotated through 180° and the remaining part of the groove inside the kiln body is welded through the cut out window.

Considering that the bands are made from carbon steels, as well as the high rigidity of edge restraint, repair performance requires preheating of the butt before welding to the temperature of 150–200 °C with subsequent local heat treatment (high-temperature tempering for relieving the residual welding stresses).

Known are the methods of repairing cracks in bands with application of automatic submerged-arc welding [14]. Edge preparation of a trapezoidal shape is performed by gas-oxygen cutting (Table, items 6–8). The groove dimensions are selected depending on the crack deviation from the generatrix of the band rolling surface, as well as the radial plane. These deviations can reach 150–300 mm. The edges are scraped with emery stone, and then run-off tabs are welded. Root pass is made by manual arc welding to 20 mm height on a copper backing plate, which is placed into the gap between the band and the kiln body, or welded into the permanent steel plate. Automatic submerged-arc welding is performed by one arc with reciprocal motion with ABC, TC-17MU type machines, or by two arcs simultaneously with A1412 machine. Welding wire Sv-08A and AN-348A flux are used as welding consumables. Local heat treatment of the finished welds is performed using non-standard put-on electric furnaces or powerful gas torches. Total duration of reconditioning operations is from 11 up to 36 days.

In the USA the narrow-gap welding technology and equipment [15] were used for repair of a through-thickness crack found in the band of a kiln in Tilden Mining Co. plant for railway pellet production (Table, item 9). The crack was cut out by two parallel cuts, placing a machine tool onto the kiln body, which had a large diameter disc saw. Dimensions of the rectangular edge preparation were as follows: width — 76.2 mm, length — 1016 mm, depth — 508 mm. A steel plate 12 mm thick was welded-in in the middle of the groove depth. Automatic welding of the groove upper part was performed with a welding tractor fitted with a head for narrow-gap welding. The groove inner part was welded-up with one wire of Lincoln L-61 grade of 2.72 mm diameter through a window cut out in the kiln body. All in all 900 layers of the weld had to be deposited. Before the start of welding butt preheating to the temperature of 150 °C was performed, and after welding high-temperature tempering at 620 °C was conducted with soaking for 10 h. Machine time for groove welding up was 14 days, and the total time of restoration work was 21 days.

The above techniques for repairing the failing bands in rotary kilns have the following essential drawbacks:

- low efficiency of welding operations;
- high labour and material costs;
- complexity of conducting the welding process;
- stable quality of the welded joint metal is not always ensured;
- unsatisfactory (extremely hard) conditions of the performers occupational hygiene.

The above drawbacks can be eliminated, primarily using ESW for repair work performance, which became quite widely accepted in repairing cracks in large-sized thick-walled metal structures and parts of machines of the metallurgical, mechanical engineering, mining, forge-and-press, rolling and other equipment [16, 17]. For instance, such unique items as a press cylinder with 9000 t force and 28 t weight made from steel 35L, sheet-bending machine roll of 750 mm diameter and 11500 mm length, broken side piece of the bed plate of a packaging press, crankshaft of the drive of the working stand of KhPT-4.5 mill, etc. were successfully repaired using consumable-nozzle ESW [17].

Conventional consumable-nozzle ESW was applied in the above examples, using multielectrode specialized equipment and high-capacity power sources, designed for operation at up to 9000 A currents. Dismantling of the unit and removal of the failed component for transportation of its parts to the production bay having the necessary welding equipment and assembly-welding bench for ESW of the reconditioned elements were performed. Such a method is highly efficient for performance of repair work conducted directly in the territory of mechanical engineering plants. It turned out to be little suitable for repair of bands of rotary kilns in their operation location, i.e. in site (practically field) conditions.

Known are the examples of repair of through-thickness cracks in the bands without dismantling them from the kiln body using consumable-nozzle single-pass ESW [18] (Table, item 11). Application of three A-1304 units with powerful transformers was required to implement such a repair technique, which runs into serious difficulties in site in terms of organizing the work performance, need to provide a power line of a high set power, as well as technique of ESW performance.

The main causes restraining the application of conventional ESW in band repair in their operation site without dismantling the latter from the rotary kiln body are:

- absence of specialized small-sized ESW equipment in enterprises operating the rotary kilns;
- absence of mobile teams having experience of efficient performance of repair-restoration operations and the necessary welding equipment;
- large consumption of time and funds for delivery of large-sized equipment for ESW;
- complexity of placing and mounting multielectrode equipment at great height (more than 20 m);
- difficulties of ensuring guaranteed fusion of the band lower edges because of the designed inclination of the kiln case to the horizon (4–5 %).

In our opinion, in order to conduct repair work under such conditions, the most promising are ESW processes, at which the metal being welded is joined along its thickness not in one pass, but by making several vertical layers in a certain sequence [19]. These processes make it easier to ensure a guaranteed fusion of the lower edges, despite the increase of machine welding time (compared to traditional single-pass ESW). It becomes possible to improve the mechanical properties of the welded joint metal due to the effect of auto-heat treatment of the previous layers by subsequent layers [19]. Another important fact is that at multilayer electroslag welding simple mobile small-sized equipment and low-power sources can be used, which are available practically in all the enterprises operating large machines and mechanisms.

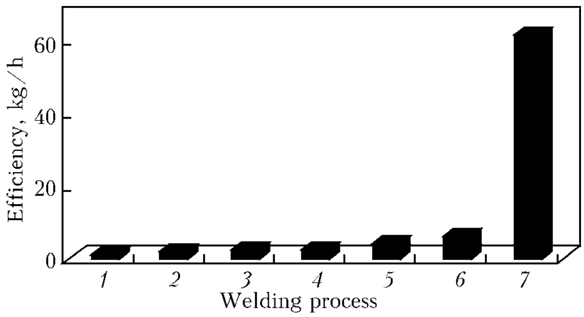


Figure 7. Dependence of efficiency of repair of through-thickness cracks in rotary kiln bands on the applied welding processes: *1* — narrow-gap automatic submerged-arc welding; *2* — coated-electrode manual welding; *3* — flux-cored wire mechanized welding; *4* — automatic submerged-arc welding; *5* — automatic two-wire submerged-arc welding; *6* — multilayer ESW with plug welds; *7* — consumable nozzle ESW

Known are examples of application of ESW in several passes in repair of large-sized items under production conditions [20–24]. In Germany the method of «channel» ESW has been developed [20], in which the crack cutting out was performed by making a number of rectangular holes of 70×32 mm size formed by slots on the abutted edges with 10 mm thick partitions of the base metal between them. Welding was performed by a consumable or non-consumable tubular nozzle with application of electrode wire of 2.5 mm diameter. This method was used to weld up a through-thickness crack in a hammer block. Before the start of welding general heating of the latter up to the temperature of 400 °C was performed, and then successive welding up of 20 channels by the electroslag process was performed. Known is an ESW process [21], when the crack is cut out to its entire depth by drilling holes of 40 mm diameter, leaving 10 mm thick bridges of the base metal. Also known is a technique when welding of each hole is performed by a rotating tubular consumable nozzle, through which welding wire is supplied eccentric to its axis [22]. Multilayer ESW welding process by the «well» method has been developed [23], in which the crack is cut out by drilling holes of 50–75 mm diameter, leaving 20–25 mm thick bridges, and hole welding up is performed by a tubular consumable nozzle, through which three electrode wires are supplied. This method was used in the Seversk Pipe Plant to repair a bed plate of a rolling mill, in which two through-thickness cracks developed in the side post and base.

Known is a method [24], in which crack cutting out is performed by drilling holes of 50 mm diameter with the step of 0.8–0.9 of diameter, and welding is performed by an elongated nonconsumable nozzle with feeding of one filler wire of 5 mm diameter. This method was successfully used for repair of a not through-thickness crack in a band without taking it off the rotary kiln body [25] (Table 2, item 10). The crack was cut by drilling holes to the entire depth of its location with a step of 52–53 mm between the hole axes. Drilling was performed with a powerful radial drilling machine, which was mounted on the kiln body on specially welded-on pedestals. Before the welding start, the butt was heated by gas torches up to the temperature of 300–350 °C. In order to contain the slag pool, a water-cooled copper device was mounted in each hole, adjacent to the one being welded. Repair efficiency in this case increased 3 times, compared to manual welding, impact toughness values rose 2–3 times due to the effect of auto-heat treatment of the previous layers by the subsequent layers, and the deposited metal volume was reduced [26].

However, the above multilayer ESW methods, while having considerable advantages over the arc welding processes, also have certain disadvantages limiting the area of their application in site.

The above methods did not become widely accepted for repair of through-thickness cracks in the rotary kiln bands for the following reasons:

• low resistance of the weld layers to solidification crack formation, particularly in welding up more than 100 mm deep holes;

• complexity of cutting out the cracks by mechanical means directly on the kiln body;

• at considerable deviation of the crack from the radial direction, during its cutting out by hole drilling it is practically impossible to cover the entire area of the crack location;

• difficulty of repairing highly ramified cracks, as well as a broad crack net.

Comparative analysis of the effectiveness of the processes of through-thickness crack repair in the rotary kiln bands (Figure 7) showed that ESW is the most highly promising technology for repair of the failing bands directly in their operation site. However, its application is restrained by a number of causes given above. In order to solve the above problem, it is necessary to develop a repair process devoid of the above drawbacks.

CONCLUSIONS

1. Formation of through-thickness cracks in rotary kiln bands is promoted by high stresses caused by bending deformations, non-uniform temperature loads, violation of the rules of rotary kiln operation, presence of latent defects of metallurgical nature in the base metal, as well as defects in welded joints.

2. Failing bands of rotary kilns are repaired in their operation site by different fusion welding processes. However, the methods of through-thickness crack repair in the bands by arc welding processes are usually low-efficient and do not always provide sound welded joints, or the required conditions of occupational hygiene. Application of known ESW methods for these purposes is preferable, being however limited by a number of technical and technological difficulties.

3. The problem of repair of through-thickness cracks in rotary kiln bands can be solved by development of a set of techniques, including an effective method of edge preparation, technique of sound welding up of cracks, etc., allowing repair of highly ramified cracks.

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PULSED METAL ARC WELDING (Review)

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Analysis of the field of application of pulsed metal arc welding of different materials is presented, and peculiarities, trends and prospects of this welding process development are considered. It is shown that this method of welding is characterized by certain technological advantages in comparison with other methods of gas-shielded metal-electrode welding and is actively used in state-of-the-art high-productivity technologies.

Keywords: pulsed arc welding, metal electrode, shielding gases, aluminium alloys, carbon steels, alloyed steels, combined technologies

In recent years volume of application of the gas-shielded metal-electrode welding has significantly increased abroad in different branches of industry. Further development also received method of pulsed metal arc welding (PMAW). Originally PMAW was mainly used for joining of aluminium alloys, including special-purpose items. In this connection national specialists in welding got an impression that PMAW may be restrictedly used for joining of other materials.

It should be noted that this method of welding differs qualitatively from other metal arc welding processes, for example, modulated current or CO_2 arc welding with short-circuiting of arc gap, and is used first of all for controlling processes of melting and transfer of the electrode metal in different spatial positions in inert shielding gases or mixtures on basis thereof. It is recommended to use in PMAW current of medium values I_w = 50–350 A, at which a fine-drop controllable transfer of the metal at welding currents of the pre-critical values is possible. Necessary range of the current pulse frequency is, as a rule, 30–300 Hz.

There are two concepts for design of the arc power sources for PMAW. One of them is based on melting of the electrode metal during passage of the base current and transfer of the formed drop at the instant of the pulse feeding. According to the other one, base current just maintains burning of the arc, while pulsed current melts and transfers the electrode metal.

Many publications were devoted to peculiarities of the PMAW technology and welding equipment, by means of which this process is implemented, including those written by scientists of the E.O. Paton Electric Welding Institute [1–3]. The purpose of this work is to make a short analysis of the fields and peculiarities of application of PMAW of different materials, and trends and prospects of further development of this welding method.

In PMAW of aluminium alloys destruction of the oxide film occurs more completely in comparison with TIG welding, and tungsten inclusions are absent. Such advantages of PMAW as possibility of welding in all spatial positions when performing erection welds (a controllable drop transfer of the electrode metal), reduction of heat input into the weld metal due to low value of mean welding current, and increase of the welding speed allowed active introducing of this method for manufacturing of aluminium structures of different designation.

It is noted in [2] that application of PMAW in manufacturing of ship superstructures from the AMg6 alloy of 4–25 mm thickness in comparison with the non-consumable electrode welding allows noticeable increasing of the process productivity due to increase of the welding speed, whereby refining of the weld metal microstructure and increase of its homogeneity in comparison with welding without current pulses also take place. The authors point at the possibility of producing welds with small legs and increase of the welding speed, which causes reduction of deformation of the structures.

High quality parameters of welded joints of truck bodies from the AlZn5Mg1 and the AMg3 aluminium alloys [4], produced by PMAW in inert gases, and of welded joints of automobile semi-trailers-mineral carriers of 14 t load capacity with a body of closed type of 6.5 m length, the framework of which is sheathed by sheets from the AMg3 alloy [5], produced by semiautomatic PMAW, are ensured. Application of narrow-gap PMAW for aluminium alloys, for example the AMg6 alloy of big thickness (16, 20, 26, 30 and 50 mm), in special-purpose structures is also efficient. PMAW allows avoiding meandering of the cathode spot over walls of the slot grooving (because of manifestation of pinch-effect the pulsed arc is spatially stable) in comparison with the direct current welding. Uniform fusion of the beads with side walls and the previous layer are also ensured. Authors of [6] determined that due to reduction of the heat input and time of contact of liquid and solid phases in the fusion zone in PMAW a significantly lower content of brittle components is formed owing to higher speed of welding, which increases serviceability of welded joints. In PMAW of the AMg6 alloy specific energy of destruction of the welded specimens with sharp notch over the fusion zone is 1.5–2 times higher in comparison with the specimens, produced by the three-phase arc welding [6].

Positive experience of mastering and introduction of the commercial PMAW of the AMg6 and 1201 aluminium alloys is accumulated and used on the basis of developments of the E.O. Paton Electric Welding Institute at Russian enterprises «SPA Compozit», PA «Strela» and M.V. Khrunichev SIC. Due to application of PMAW significantly reduced number of defects on circumferential and longitudinal welds, made on the special-purpose structures.

Application of PMAW for production of special-purpose split joints of the AMg6 alloy ensures formation of a butt without a groove, which significantly simplifies machining of the edges and their preparation for welding [7]. In argon- and helium-shielded PMAW of butt joints of alloy 1201 (4 + 4) mm thick on a removable backing, split joints (4 + 10) mm thick and slot-groove joints of the alloy above 50 mm thickness, formation of a minimal heat-affected zone is achieved [8], whereby range of working welding currents is expended and necessary penetration of the metal with preservation of constant weld width and reinforcement are ensured.

The PMAW method is widely used for manufacturing of fuel tanks of flying vehicles from alloy 1201 and billets of frames from the AMg6 aluminium alloy [9]. Introduction of the helium-shielded PMAW of fuel tanks of flying vehicles from the AMg6 aluminium alloy of 70 mm thickness instead of a manual argon-arc welding ensured reduction of defects in the welds by 30–40 % and increase of productivity of the welding operations 4–5 times. In mentioned technology a source of the arc pulsed current, developed at the E.O. Paton EWI, was used, in which concept of a two-stage current pulse was implemented [10]. The stage of a low pulse current with amplitude I_l and duration t_l allows melting an assigned volume of metal on the electrode end, and the stage of a high pulse current with amplitude I_h and duration t_h makes it possible to transfer a molten drop in all spatial positions (Figure 1). Base current I_b maintains burning of arc, and smooth regulation of the welding current occurs due to change of frequency of pulses $f = 1 / t$ (where t is the period of pulses) (Figure 1).

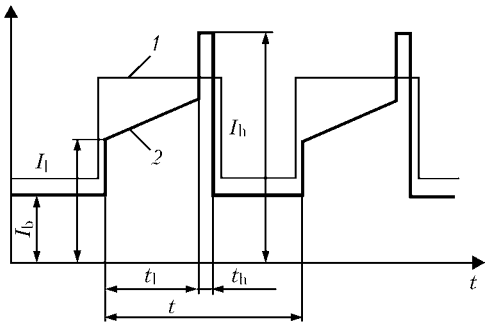

Figure 1. Pulses of welding current (current value) in PMAW: *1* — rectangular ones; *2* — double-stage ones

It is known that in welding of carbon and low-alloy steels sputtering of metal is one of important parameters of the process. In CO_2 welding (depending upon dynamic characteristics of the arc power source, electrode wire diameter and welding current) range of the electrode metal melting and sputtering loss equals 4.5–12.0 %. In direct current welding in the argon-base mixture, for example Ar + 18 % CO_2, this parameter reduces to 2.5–6.5 %, and in PMAW in the same mixture losses are even less (1.0–1.5 %). Sputtering of metal in such method of welding does not depend upon welding current and diameter of the electrode wire, and at optimal for these conditions parameters of the pulses it remains minimal within the whole range of welding currents [11]. It is noted in [12] that PMAW may be recommended for welding of metal structures from low-alloy steels, on which presence of sputter of the electrode metal is not allowed; it may be also used for welding of thin-sheet metal and fulfillment of the small section welds, as well as for welding and surfacing, if it is necessary to ensure a small share of base metal in the weld metal. High level of mechanical properties of metal of the welds, produced on steels of 09G2S and 15G2AF type, is achieved due to insignificant content of non-metal inclusions and formation of a favorable structure with prevalence of acicular ferrite, whereby more fine-grained structure of the weld metal than in welding by a stationary arc is formed, and high values of the weld impact toughness at negative temperatures are noted [13]. Efficient application of automatic PMAW in the Ar + 18 % CO_2 mixture, using wire of 1 mm diameter for manufacturing of the reduction gear components is described in [14].

PMAW allows improving welding of alloyed steel in vertical and overhead positions. Due to improvement of the welding process stability and fine-drop transfer of the metal, a qualitative welding may be performed at the currents, having values below the critical one, which allows joining thin metal by wires of 1.6 and 2.0 mm diameter. It is established that propensity of metal of the welds, produced on the Kh18N10T steel, to formation of pores and slag inclusions in PMAW is lower than in conventional TIG welding [15]. Microstructure of the weld meal is refined in comparison with the one produced by a conventional welding, and reduction of the heat-affected zone is observed, whereby mechanical properties of the weld metal are at the level of the welds, produced by the non-consumable electrode welding.

As it is known, formation of hot cracks on steels may be reduced due to application of the conditions with minimal release of heat [16]. As far as in PMAW mean values of the welding current are lower than in direct current welding, and application of wires of bigger diameter is possible, hazard of formation of hot cracks reduces. Semi-automatic PMAW of alloyed steels, sensitive to formation of hot cracks, especially when thickness of the items is big, is efficient. In [17] example of application of PMAW is shown for production of welded joints of G-X5CrNi 174 (17 % Cr and 4 % Ni) and TTSt E 355 steels without hot cracks on a spiral body of the high-pressure pump turbine.

In this work also technological peculiarities and advantages of PMAW of the unloading auger from chrome-nickel steel and elements of blades of a big-size mixer from the X10CrNiMoTi 1810 steel are described. It is noted that PMAW is used in all spatial positions of bearing structures from chrome-nickel alloys of 10–40 mm thickness.

PMAW equipment and technology are used for joining copper- and titanium-base alloys. Argon-shielded PMAW was used in welding up of cracks and cavities on components of ship devices from copper alloys without demounting. It is noted in [18] that in argon-shielded PMAW of the LMtsZh55-3-1 brass and the BrAMts9-2 bronze of 16–24 mm thickness in vertical and overhead positions, formation of welds improved, probability of occurrence of lacks of fusion reduced, and microstructure of the weld metal got refined.

Fine-drop transfer of metal and reduction of critical welding current in PMAW acquire special significance in production of titanium compounds for ensuring reliable protection of the welding zone [19]. As speed of welding increases, width of the metal heating area and time of its stay at high temperatures reduce, which causes reduction of welding deformations and improvement of conditions of protection against oxidation of the weld metal and back side of a welded joint. The authors state in [20] that in PMAW of titanium sheets of 6 mm thickness, to which ribs with V-shape asymmetrical groove preparation were welded in free state, productivity increased and angular deformations significantly reduced (2 times in comparison with manual non-consumable electrode welding). Mechanical properties of the welded joints were not inferior to those of the joints, produced by argon-arc welding. PMAW allows performing welding of titanium alloys under erection conditions in different spatial positions; stabilizing penetration; practical removing of sputtering; and ensuring high parameters of ductility, strength, and impact toughness [21, 22].

Development of the pipeline transport in addition to high requirements to mechanical properties of welded joints and increase of productivity of welding operations requires for application of advanced high-technology methods of welding. In Canadian Welding Institute PMAW with a system of the arc length control was developed [23]. It is informed in [24, 25] that application of PMAW of position butt joints with a patented function of the arc control allowed during construction of the main pipeline reducing the number of defects of lacks-of-fusion type due to improvement of the metal transfer characteristics, and increasing ductility of metal of the welds at critical opening of the crack apex.

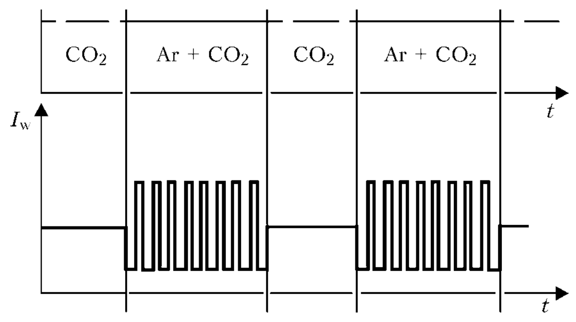

Figure 2. PMAW scheme with modulation applied to current and kind of shielding gases

In [26] PMAW of root welds, using flux-cored wire with metal core in the mixtures of Ar + 20 % CO_2 or Ar + 15 % CO_2, as well as Ar + 1–5 % O_2, is proposed. Such technology allows avoiding defects of the lacks-of-fusion type and makes it possible for the welder to control length of the arc. In contrast to the solid wire, a wire with a metal powder enables production of a wider welding arc, whereby fusion increases and advantages of the controllable transfer of metal are used.

Experience of application of PMAW with alternate feeding of shielding gases is known [27, 28]. Such method of welding of a low-alloy steel, for example 09G2, allows, in comparison with just PMAW or direct current welding, reducing size of grains in the area of overheating and increasing content of acicular ferrite [27]. Scheme of such process is presented in Figure 2, whereby frequency of feeding of shielding gases into the welding zone is 1–5 Hz.

Lately, so called double-arc PMAW is actively introduced for gas-shielded method [29, 30]. The «Fronius» company is one of the leaders in implementation of the twin-arc pulsed welding on the «Time Twin Digital» installation. Recommended areas for application of such installation are not just automobile industry and construction of pipelines, but also ship building, including operations in high sea.

In Krenfield University (Great Britain) automated welding of pipelines under complicated environmental conditions and at low temperatures was developed. It is noted that application of pulses with respective parameters allowed increasing productivity of welding of position butt joints in construction of pipelines [30].

In [31] process of pulsed twin-arc welding of aluminium alloys is investigated, and on the basis of the results obtained the conclusion is drawn on expediency of its use in single-pass welding of butt, split, T- and overlap thin sheet joints, when it is necessary to produce welds with big legs.

At present there is no common opinion about methods of stabilization of pulsed arcs in the twin-arc welding. Different versions are proposed, for examples, antiphase modes, a very small phase shift, or absence of the latter. In [32, 33] method of synchronization of the pulses with about 0.5 ms lag of pulsed current of rear arc relative the front one is described, whereby control of the front arc length is performed by a system of the frequency-pulse modulation, and of the rear arc length — by a system of the pulse amplitude lag. Attention is paid to such important factors as distance between the arcs and allowable content of CO_2 in the argon-base mixture. It is established in [34] that in the twin-arc welding by the pulsed arcs of low-carbon and stainless steels, a significant phase shift (up to

1 ms) between the arcs is necessary for ensuring of the process stability.

At present the method of laser-arc welding is being developed, which allows, in comparison with conventional gas-shielded welding, achieving high speeds of welding and getting deeper penetration and good mechanical properties of welded joints, whereby application of the arc process reduces power of the laser beam, which causes cost reduction of the whole installation. Such technologies are used in automobile industry [35]. Due to low sputtering characteristic of PMAW, application of this method in mentioned technologies is more advantageous, because soiling of the laser optic system is excluded. Experience of application of high-speed welding (twin-arc PMAW + pulsed arc-laser) of big-thickness sheets exists. In this technology three pulsed arcs with a metal electrode are used [36].

So, review of fields and scale of PMAW application proves high efficiency of this method application for joining of different materials, when it is necessary to ensure controllable transfer of the electrode metal in all spatial positions with small sputtering losses. Actuality of application of this welding method is confirmed by state-of-the-art development of technology and welding equipment on it basis.

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PRESENT MARKET OF LASER EQUIPMENT FOR WELDING AND PROCESSING OF MATERIALS

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Present state and level of production of industrial lasers and laser systems for processing of materials and volume of the world and regional markets of laser equipment and of the laser welding equipment market are considered.

Keywords: industrial lasers, laser systems, production, market, welding equipment

• Laser equipment and laser technologies represent state-of-the-art dynamically developing scientific-technological area, which determines to a great degree level of different fields of application, including medicine, informatics, telecommunication, and processing of materials. Laser technologies became the basis of innovation development of many high-tech branches of industry, for example, automotive industry, while state-of-the-art microelectronics is in general impossible without laser technologies. To put it in other words, application of laser and laser systems in processing and joining of materials caused occurrence in a number of cases of the alternative-free fields of their practical application and created conditions for implementation of principally new design-technical solutions.

Universality of laser radiation as a technological tool manifests itself in the fact that it may be used for fulfillment of a whole number of technological processes — cutting, welding, heat treatment, surface alloying, piercing of holes, cleaning of surfaces, surfacing, marking, etc. Application of fiber optics for transportation of the beam significantly expands technical-technological possibilities of laser systems [1].

Table 1. Structure of world market of lasers and laser systems by fields of their application (2006) [2]

Fields of application	Lasers, bln euros	Laser systems, bln euros
Telecommunication	1.21	9.5
Processing of materials	2.0*	5.8**
Microlithography	--	5.1
Information technology (office and domestic equipment)	1.29	21.0
Medicine	0.54	1.3
Scientific researches and developments	0.41	2.0
All together	**5.45**	**44.7**

*Including microlithography.
**Not including lasers and laser systems for microlithography.

Laser equipment and material processing technology ensure high productivity of labor and quality, saving of energy and materials, expand possibilities of application in structures of difficultly processed materials and at the same time guarantee environmental cleanliness of production. These and other factors enabled wide and efficient field of application of technological lasers and laser systems in welding production.

• State-of-the-art laser equipment is represented on the world and regional markets by two big groups — lasers and laser systems [2]. They are designed directly for processing of materials and classified as industrial or technological lasers and laser systems. Industrial lasers, in their turn, are divided into two classes: laser systems for macroprocessing of materials, which include systems for welding, cutting, marking, engraving, processing, hardening, and processing of the material surface; laser systems for microprocessing, which include systems used in semiconductor industry, production of microelectronics and printed circuits, and systems on excimer lasers for microlithography.

In 2006 general volume of sales of lasers and laser systems constituted about 50 bln euros. Sector of industrial lasers and laser systems for processing of materials is comparatively small on the world market and constitutes about 15 %, but rates of its annual growth are sufficiently high. So, volume of sales increased within last 10 years by 180 %. General structure of the world market of lasers and laser systems by fields of their technological application is presented in Table 1.

Rather full and authentic idea about present state of the world market of industrial lasers and laser systems gave results of marketing investigations, carried out on initiative of the journals «Industrial Laser Solution» [3] and «Laser Focus World»*. According to the data of these investigations, 37,525 units of in-

*Results of marketing investigations of the «Optech Consulting» and «Industrial Laser Solution» companies, presented in this article, have certain discrepancies.

Table 2. World market of industrial lasers and laser systems [3]

Name	2005	2005 / 2004, %	2006	2006 / 2005, %	2007*	2007 / 2006, %
Number, pcs	35,165	12	37,525	6	39,955	6
Lasers, mln USD	1,241	6	1,322	6	1,405	6
Laser systems, mln USD	4,318	16	4,710	9	5,150	9
*Forecast estimation.						

dustrial lasers and laser systems at the sum above 6 bln USD were sold on the world market in 2006. In Table 2 the data are presented, obtained due to these investigations, on volumes of sales and dynamics of their growth within the period 2005–2006, and forecast for 2007 is made.

According to estimations of the experts, the year 2006 was successful for producers of industrial lasers and laser systems. Income from sales of industrial lasers increased on average by 7 %, and of the laser systems — by 9 %. The same rate of development of the industrial laser market (6–9 %) is forecasted for 2007. It is expected that volume of sales in 2007 will constitute about 40 thou units of the equipment. In their assessment of the market of industrial lasers in 2006 the experts note that almost all produced lasers were sold in the composition of laser systems, i.e. on the world market already exists a certain deficit of single-unit lasers, necessary, in particular, for their replacement in repair of technological systems.

The last decade is characterized not just by growth of production of technological lasers, but also by increase of the number of their types and expansion of the range of their power and technological possibilities. In Table 3 quantity data on world production of main types of industrial lasers are presented, including those designed for laser technological systems [3].

For present dynamic laser market continuous redistribution of production volumes of different types of lasers are characteristic. So, production of CO_2-lasers still preserves its leading position on the laser market and sufficiently high growth (9 %) (Table 3), which is stipulated by increase of the demand for low-power CO_2-lasers, volume of sales of which in 2006 constituted almost 60 % of general number of solid CO_2-lasers.

In sector of solid industrial lasers (on the basis of alumoyttrium garnet with optical lamp or diode pumping) noticeable reduction of production (–14 % in 2006) and volume of sales (9 % in 2006) take place. It is connected first of all with growth of production of the progressive fiber lasers, which constituted 5,450 units in 2006 or 57 % of their production volume in 2005 (see Table 3).

In sector of low-power technological lasers, fiber lasers at present seriously compete with solid lasers with optical pumping, taking away from them a significant share of the market, especially in the group of technological lasers for marking. Powerful fiber lasers are a real alternative to powerful CO_2-lasers, in particular due to their higher efficiency, stable output power, small production area, possibility of the laser beam transportation over optical light guide at the distance up to 300 m. Dynamics of the fiber laser segment corresponds to this situation: the specialists forecast in 2007 quantitative growth of their production by 31 %.

Production of diode and excimer lasers of 1–4 kW power («Other» in Table 3) increased in 2006 by 16 %, and in future this segment of the laser market will, evidently, preserve annual increment on average by 8–12 % [3].

While in Table 3 quantitative estimation of the world market of industrial lasers and laser systems and its structure are given, in Table 4 cost parameters of sales of main types of single-piece lasers and laser systems are presented.

Using data of Tables 3 and 4 one may also judge about average cost of industrial lasers of different types and power, and one may also see that average cost of a complete laser system exceeds approximately 4–5 times cost of a single-piece laser of the same type. Presented data (see Tables 3 and 4) also reflect undergoing restructuring of the market of industrial lasers both among its separate sectors and inside each of them, which is connected not just with conjuncture of the demand, but to a significant degree with growth of production and consumption of the advanced fiber lasers. This is also reflected in the statistical information: producers and experts in marketing considered

Table 3. World volume of production of industrial lasers, pcs [3]

Type of laser	2005	2006	2006 / 2005, %	2007*	2007 / 2006, %
CO_2	19,940	21,800	9	23,320	7
Solid	11,275	9,725	–14	9,285	–4
Fiber	3,475	5,450	57	6,750	31
Other	475	550	16	600	9
All together	**35,165**	**37,525**	**7**	**39,955**	**6**
*Forecast estimation.					

Table 4. Volume of sales (mln USD) on world market of laser equipment in 2006 and 2007 [3]

Type of laser	Lasers				Laser systems			
	2006	2006 / 2005, %	2007*	2007 / 2006, %	2006	2006 / 2005, %	2007*	2007 / 2006, %
CO_2	696	10	751	8	2,545	9	2,850	12
Solid	431	–9	411	–5	1,680	0.3	1,670	–0.06
Fiber	147	61	190	29	380	65	495	30
Other	48	20	53	10	105	21	127	20
All together	**1,322**	**7**	**1,405**	**6**	**4,710**	**9**	**5,142**	**9**

*Forecast estimation.

it necessary to single out fiber lasers from general volume of production and sales of the solid lasers into an independent sector.

• Development of fiber lasers is one of the most significant achievements of state-of-the-art laser physics and fiber optics at the close of XX century, which allowed designing a new high-tech instrument for processing of materials. Further this type of industrial lasers is considered in more detail.

CW fiber lasers on the basis of active fiber light guides, doped by ions of rare-earth metals (ytterbium and erbium), are characterized by a number of essential advantages in comparison with traditional lasers, which, in particular, have no competitors in the field of laser welding, cutting, and drilling. Wavelength of the fiber laser with ytterbium doping of the optic fiber is $\lambda = 1.07$–1.12 μm, which ensures more efficient interaction of the radiation with metals than radiation of CO_2-lasers ($\lambda = 10.6$ μm). In fiber lasers unique quality of the output beams is achieved, which is determined by the beam parameter product (BPP) or the beam transformation constant Q; for fiber laser of $P = 10$ kW BPP (Q) < 4.5 mm·mrad [4–7].

In Table 5 comparison of main technical parameters of CW lasers of different types is given, which allows clear demonstrating of advantages of the fiber lasers [4].

The most significant and, perhaps, the only factor, which limits wide use and therefore implementation of powerful technological fiber lasers, is their high cost. As far back as several years ago their cost was 150–450 USD for 1 kW of power, but in 2006 a trend started to show of cost reduction of single-piece lasers. Fiber lasers are characterized by high compactness; overall dimensions of the base (1 kW) module (of YLR-1000 type) are $60 \times 79 \times 110$ cm. Small dimensions and mass of lasers of this type and air or water cooling with very low consumption of water ensure their high mobility and operation attractiveness. In addition, a powerful fiber laser, equipped with optical switch, may serve simultaneously from 2 to 6 technological installations for welding or cutting, whereby general cost of such complex is significantly lower, if one compares it with a set of technological installations, each of which is equipped with its own laser [1, 7].

Powerful fiber lasers ensure single-pass welding of steel of 4 mm thickness at speed 7 ($P = 6.9$ kW) and 4 m / min ($P = 4.0$ kW). Fiber lasers also allow performing high-quality cutting of metal at 3–5 times higher speed than by CO_2-lasers of the same power. So, even relatively low-power ($P = 100$ W) fiber lasers allow cutting steel of 1.5 mm thickness at speed 4 m / min [4]. At present in a number of countries

Table 5. Comparison of industrial lasers of different types [7]

Parameter	Required for application in industry	CO_2-lasers	Nd:YAG with lamp pumping	Nd:YAG with diode pumping	Diode lasers	Fiber lasers
Output power, kW	1–30	1–30	1–5	1–4	1–4	1–30
Wavelength, μm	As short as possible	10.6	1.064	1.064 or 0.03	0.80–0.98	1.07
BPP, mm·mrad	< 10	3–6	22	22	> 200	1.3–14.0
Efficiency, %	> 20	8–10	2–3	4–6	25–30	20–25
Range of radiation delivery by fiber, m	10–300	–	20–40	20–40	10–50	10–300
Stability of output power	As high as possible	Low	Low	Low	High	Very high
Sensitivity to retroreflection	As low as possible	High	High	High	Low	Low
Occupied area, m^2	As little as possible	10–20	11	9	4	0.5
Cost of maintenance, rel. units	Same	1.0–1.5	1	4–12	4–10	0.1
Periodicity of replacement of lamps or laser diodes, h	As long as possible	–	300–500	2000–5000	2000–5000	>50,000

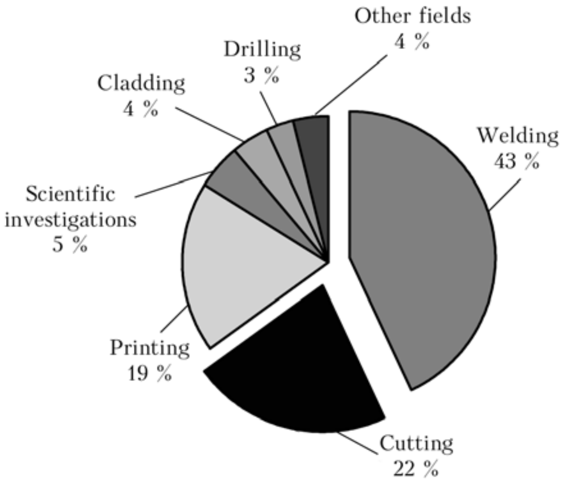

Figure 1. Structure of world market of technological fiber lasers by fields of application (2006) [6]

innovation projects are carried out, directed at development of efficient welding technologies on the basis of powerful fiber lasers and in combination of the latter with electric arc or plasma (hybrid processes) for production of welded pipes of big diameter (1220–1420 mm) and in the field of ship building, energy and transport machine building, aerospace production, etc.

Technological and in many cases economic advantages of fiber lasers ensure nowadays significant general potential for growth of the whole market of industrial lasers and laser systems. In opinion of the experts, average annual rate of increment of the fiber laser sector within 30–40 % will preserve in immediate prospect, and in near future volume of sales of fiber lasers, which have rather high single-piece cost, will achieve the level of 1 bln USD [4]. Such growth is accompanied by expansion of the areas of technological application of fiber lasers (Figure 1).

• Equally with consideration of general characteristics of the world market of industrial lasers and laser systems of interest is also, undoubtedly, regional distribution of their production and consumption. General pattern of distribution of the production volumes of industrial lasers and incomes from their sales in such three regions of the world as Western Europe, North America and Eastern Asia (China, Japan and Republic of Korea) are presented in Figure 2.

Figure 2 visually demonstrates that main region-producer of industrial lasers is North-American region (USA and Canada), in which production of more than half (51 %) of general amount of supplied on the market industrial lasers is concentrated. Second position occupies Western Europe, and third position — countries of Eastern Asia. As to the cost volume or income, first position occupies Europe (46 %), which is connected with different specialization of enterprises of these three regions in production of different types of industrial lasers that differ significantly by the cost of a production unit.

Structure of world production of different types of industrial lasers and laser systems in three mentioned regions is presented in Figure 3. North America

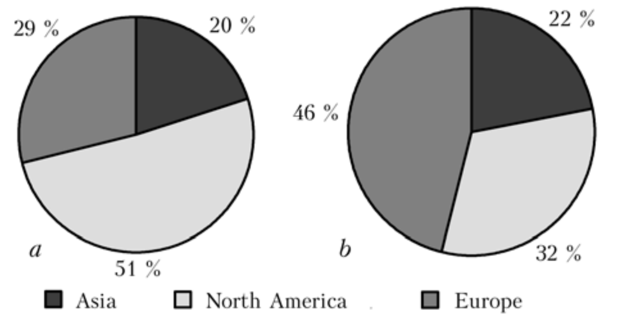

Figure 2. Share of volume of production (*a*) and sales (*b*) of industrial lasers by regions of world (2006) [3]

is indisputable leader as to the number of produced and supplied to the market industrial lasers, including 82 % of fiber and 57 % of CO_2-lasers. From the total number of the latter low-power lasers constitute up to 80 %. Exactly significant growth of the number of produced in North-American region low-power lasers allowed increasing in 2006 share of sales up to 32 % (see Figure 2, *b*), which is by 2 % more than in 2005. In the same region rather significantly develops production of solid YAG (35 %), excimer and diode (semiconductor) (34 %) low-power lasers (see Figure 3).

Second position in the world in production of industrial lasers and laser systems confidently occupy EU countries (15 %), except fiber lasers. Europe dominates in production of powerful solid lasers (42 and 61 %) (see Figure 3) and powerful CO_2-lasers, there share in the volume of world-wide supplies (23 %) being comparatively small. High share in sales of first of all powerful solid lasers, which have a significant cost, put Western-European region into the leaders as to the general cost volume of sales (46 %) (see Figure 2, *b*) of industrial lasers.

Share of the Asian region countries in volumes of production of technological lasers and systems and cost volumes of their sales in 2006, as well as in previous years, constituted 22–23 % (see Figure 2, *a*) of the world-wide volume of sales, whereby (see Figure 3) approximate parity in production of CO_2- (20 %) and solid (28 %) lasers preserves.

Industrial lasers and laser systems constitute a significant share in foreign trade. The biggest world producers of technological lasers, characterized by a certain specialization, are located in Germany, USA, and

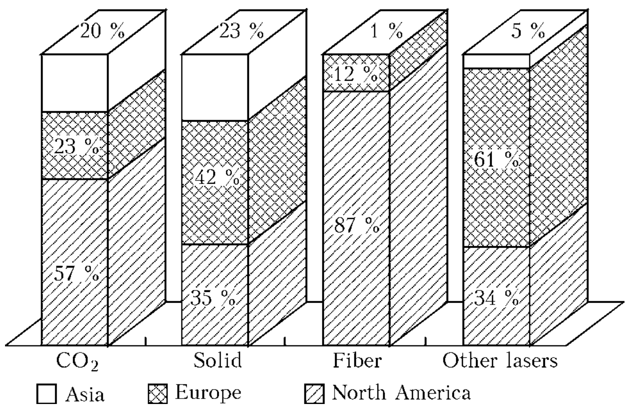

Figure 3. Structure of production of industrial lasers and laser systems in separate regions of world (2006) [3]

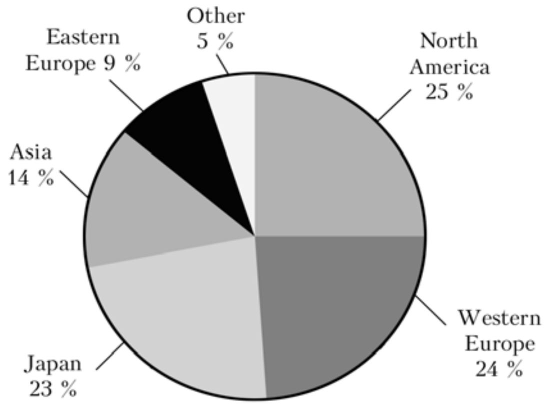

Figure 4. Share of installed in 2006 industrial lasers and laser systems in separate regions of world [3]

Japan. This is reflected in volumes of sales of lasers and laser systems both for internal consumption and for export. In Figure 4 the data are presented, which reflect share of installed in 2006 industrial lasers and laser systems in different regions and countries of the world.

First of all of interest is the fact that more than one third (37 %) of the world production of industrial lasers and laser systems are consumed by the countries of Eastern Asia, the main share (23 %) being consumed by Japan, and 14 % — by such countries as China, Republic of Korea and India. In 2006 practically the same volumes (in term of cost) of industrial laser systems were shown for North America (25 %) and Western Europe (24 %). In North America main consumers are leading branches of US industry, while in Western Europe — German industry. The share of Germany is more than 35 % of the all-European volume of consumption and installation of industrial lasers and laser systems. Then according to the number of installed in 2006 technological lasers go Spain, France and Belgium. In Italy, Great Britain and Switzerland reduction of the volume of purchases of laser systems was noted in 2006.

Taking into account growth of investments on the side of EU into countries of Eastern Europe, in recent years volumes of purchase by the industrial companies of laser systems increased by up to 9 % in this region [7]. Into the number of «other» countries (Figure 4), the share of which constitutes 5 % of the general number of installed laser systems, enters Russia — one of few CIS countries, which preserved scientific-technical potential in the field of laser technologies, which corresponds to the level of world leaders. Capacities, which produce laser equipment, gradually increase in Russia: laser and fiber optic equipment is at present produced by more than 200 Russian enterprises, which supply mainly on the internal market more than 190 models of laser technological equipment [8, 9].

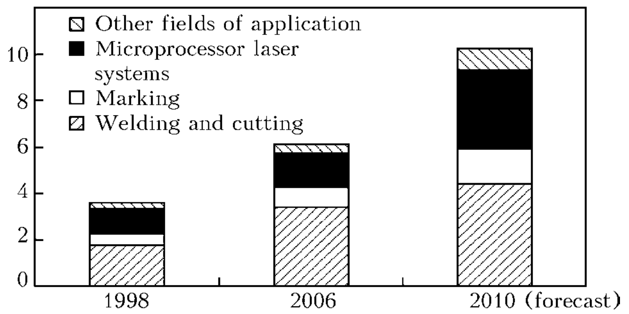

Figure 5. Volumes of sales C on world market of industrial laser systems for processing of materials [2]

• In 2006, as it was noted above, on the world market of industrial laser systems 87 % constituted laser macrosystems and only 13 % — microsystems. Among industrial laser macrosystems dominate technological macrosystems for marking and engraving — 44 % of the whole number of produced laser systems. Significant share is occupied by industrial laser systems for cutting (25 %), welding (12 %), and surface processing and piercing of holes (3 %).

In Figure 5 cost structure of the market of industrial laser systems for main material processing technologies and trends of its change within the period 1998–2010 are presented. Main share of sales on the world market (about 50 %) constitute laser systems for cutting, welding and other relative technologies, of which almost 2 / 3 of the income constitute laser systems for cutting and piercing of metal materials.

According to estimations of the experts, it is expected in 2007 that amount of sales of industrial lasers and laser systems will increase, as a whole, by 6 % and will constitute about 40 thou units. Incomes from sales of industrial lasers will increase by 6 % and of the industrial laser systems — by 9 %. It is noted that growth of the market will continue exactly in the key sectors — cutting / welding of metal, marking / engraving and microprocessor technological systems.

As it was noted above, main producer and consumer of industrial lasers and laser systems in European region is Germany; this country also has the most powerful scientific-technical potential in the field of investigations and development of new laser systems and technologies. Germany is one of first industrially developed countries, which singled out laser and laser systems for welding and relative technologies as an independent sector on the internal national market of welding equipment [10]. In this connection reviewing of German market of lasers and laser systems is also of a certain interest. According to estimations of German specialists, all-European market of welding equipment achieved 11 bln euros in 2003, and German internal market — 3.6 bln euros, whereby volume of sales in the sector of welding lasers and laser systems constituted more than 340 mln euros (442 mln USD).

Results of the European welding market analysis and, in particular, sector of lasers and laser systems, made by the «Frost&Sullivan» company, somewhat differ from estimations of German experts, but are also of a certain interest [11, 12]. So, according to the data of the «Frost&Sullivan», European market of laser equipment for welding and relative technologies constituted 542.8 mln USD in 2004, and by 2011 growth of sales up to 802.2 mln USD is forecasted. As it was noted above, main share of European market of laser welding equipment, including cutting, is occupied by the market of Germany, on which in 2004 volume of sales of laser equipment for welding production constituted 357.7 mln USD or 65 % of European market. It is forecasted that by 2011 German internal market of laser equipment for welding and relative technologies will achieve 481.1 mln USD [13].

Italian market of laser welding equipment occupies second position in Europe as to the volume of sales. In 2004 its incomes achieved 41.8 mln USD; by 2011 their increase up to 77.7 mln USD is forecasted [14].

Incomes of the welding equipment market of Great Britain constituted 32 mln USD in 2004; by 2011 the «Frost&Sullivan» forecasts their growth up to 50.5 mln USD [15].

Investigation of possibility of application of the laser welding technology in new high-tech fields of industrial application is an additional pulse for expansion of the market. Many of these technologies are at present in the state of active development, and they, undoubtedly, will play important role in formation of the market within 2007–2011. Development of new laser sources and improvement of the existing laser equipment strengthen potential possibilities and advantages of the laser welding application in many branches of industry. Expenses for introduction of the laser welding reduce, and advantages from application of this technology increase, which stipulates growth of the number of potential consumers of the equipment for laser welding. Promising fields for application of laser welding, in addition to automotive industry, are such branches as heavy and transport machine building, ship building, airspace industry, and production of welded pipes of medium and big diameters.

• Convincing and visual demonstration of growth of the world laser market became international exhibition «Laser 2007», which took place in June in Munich (FRG). 2,000 companies and organizations from 90 countries of the world, expositions of which presented the newest developments in the field of laser equipment; specimens of serially produced lasers and laser systems with output power from 1 to 20,000 W and separate units and elements of these systems; original examples of application of lasers for processing of materials, etc., took part in work of the exhibition. It is characteristic that just several years ago such leading world producers of lasers and laser systems as Rofin, Trumpf, JPG, Dilas and other companies oriented themselves at own development and complete production of laser systems, and at present the situation has drastically changed. In many countries were established and increase their production capacities specialized small and medium companies, which develop and produce elements and separate units for laser macro- and microsystems in 20 specific technological directions. At the exhibition «Laser 2007» expositions of 113 companies were presented. Such situation on the laser market allowed big companies-producers passing over to wide cooperation, which could not but cause reduction of the terms of manufacturing of laser systems and certain reduction of their production cost. Presence of small narrowly specialized companies expanded and made cheaper maintenance and repair of acting technological laser systems.

One more not less significant trend of development of present world laser market is essential reduction of cost of lasers of all types with preservation of the peculiar for a dynamic market fluctuation of prices. This is connected with both conjuncture of the market and with level of solvency of production associations and companies-consumers in different regions of the world. On average «specific» cost of state-of-the-art lasers is 50–175 euros / W. As an example of approximate cost of separate types of lasers the following data may be presented: 1–2 kW CO_2-laser of series SM costs 50 euros / W; 1–2 kW CW Nd:YAG laser costs 75–90 euros / W, and of 3–6 kW power — 120–175 euros / W; while average price of YLR fiber lasers is 100–120 euros / W.

In the conclusion it should be noted that world market of laser equipment for processing of materials has excellent prospects and reflects ever growing need of the industrial production in this advanced and efficient equipment and technology. In its turn sector of technological lasers for cutting, welding and processing of materials has the highest rate of development on the world and regional markets of welding equipment. Continuous expansion of volumes of production and consumption of technological lasers enables, undoubtedly, expansion of branches and volumes of industrial application of this advanced material processing technology — technology of XXI century.

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EFFECT OF TITANIUM ON CRACK RESISTANCE OF DEPOSITED CARBON METAL

A.P. ZHUDRA, S.Yu. KRIVCHIKOV and **V.V. PETROV**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Results of experimental studies into the effect of alloying with titanium (up to 1 wt.%) on crack resistance, structure and hardness of low-alloy carbon metal deposited by using self-shielding flux-cored wire are given. It is established that increase in the titanium content is accompanied by growth of continuity and branching of the carbide-cementite phase in the deposited metal, and by increase in its resistance to microcracking.

Keywords: cladding, self-shielding, flux-cored wire deposited carbon metal, crack resistance, microstructure, alloying with titanium, hardness, microhardness

The E.O. Paton Electric Welding Institute has developed and widely applies now a self-shielding flux-cored wire of the PP-AN160 grade, which is designed for repair of worn-out parts made from gray and high-strength cast iron (crankshafts of internal combustion engines, seats of shafts, casing components, etc.) [1]. In deposition of metal without preheating and concurrent heating, when the rate of cooling of the deposited metal within a temperature range of probable formation of cold micro- and macrocracks (450–250 °C) may amount to 12–14 °C / s [2], its crack resistance substantially decreases.

The purpose of this study was to experimentally investigate the effect of a low content of titanium on crack resistance of the deposited carbon metal produced by cladding using self-shielding flux-cored wire PP-AN160.

1.8 mm diameter flux-cored wires with a titanium content of the core varied discretely through varying the weight content of ferrotitanium FTi70S08 (GOST 4761–91) were made for the investigations. Constant values of the filling coefficient of the flux-cored wires with increase in the ferrotitanium content were provided by decreasing, accordingly, the weight content of an iron powder.

Multilayer cladding of the beads was performed on steel plates without preheating under the following conditions: I_{cl} = 170–180 A, U_a = 19–21 V, v_{cl} = = 14 m / h, direct current, reverse polarity. Each next bead was deposited after complete cooling down of the previous one. The clad samples had the following chemical composition in the third layer, wt.%: 2.2–2.4 C, 0.7–0.8 Mn, 1.6–1.8 Si, 0.2–0.3 Cr, 0.07–0.14 horophilic element, 0.2–0.3 Al, and 0.03, 0.08, 0.17, 0.34 and 0.72 Ti. Specimens of the deposited metal for metallographic analysis and for obtaining comparable results were taken at the same distance from the beginning of each bead, where the cladding process conditions were considered the steady-state ones.

Metallographic examinations showed that titanium affected the quantity and morphology of microcracks in the deposited metal and fusion zone. Microcracks of a big length and high opening degree were revealed in the specimens containing 0.03 % Ti (with the flux-cored wire containing no FeTi). They were found both in the deposited metal and in the fusion zone. And some of them propagated into the heat-affected zone. With increase in the titanium content, the quantity, length and opening degree of microcracks decreased. Individual microcracks located directly in the deposited metal were detected in the specimens containing 0.17 and 0.34 wt.% Ti. Increase of up to 0.72 wt.% in the titanium content had no

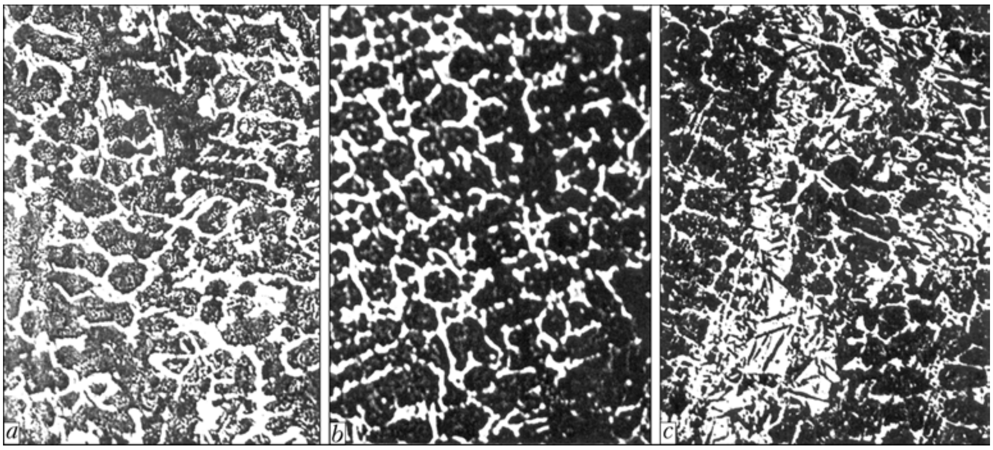

Figure 1. Microstructure of specimens of deposited metal with titanium content of 0.03 (*a*), 0.34 (*b*) and 0.72 (*c*) wt.% (×320)

substantial effect on crack resistance of the metal investigated.

The effect of titanium on formation of microcracks in the deposited metal may be related to changes in its structure. The structure of metal of the specimens with 0.03 wt.% Ti consists of austenite decomposition products (ferrite-pearlite mixture) and a carbide-cementite phase, which has the form of a branched reinforcing network in plane of a section. Regions of ledeburite eutectic, having a honeycomb structure, are also present, this being characteristic of low-alloy foundry hypoeutectic cast iron. Alloying with titanium within the ranges investigated exerts no substantial effect on the dispersion degree of dendritic structure, but changes the spatial structure of the carbide-cementite network and phase composition of the deposited metal. At the 0.03 wt.% Ti content, the network is found not in all the regions of interaxial spacings of dendrites, and has a discontinuous form (Figure 1, *a*). Branching and continuity of the network considerably grow with increase in the titanium content (Figure 1, *b*). Increase of up to 0.72 wt.% Ti has no marked effect on structure of the carbide-cementite network, but leads to formation of relatively large martensite regions in the deposited metal (Figure 1, *c*). It can be assumed that resistance of the deposited metal to cracking increases as a result of a substantial growth of the dispersion degree of the reinforcing carbide-cementite network formed at a titanium content of 0.2–0.4 wt.%.

In addition to increasing in crack resistance, titanium also affects hardness HV of the deposited metal and microhardness H_μ^a of the austenite decomposition products, the values of which first decrease, and then start growing (Figure 2). According to the data of study [3], this change in the H_μ^a and HV values is related to a dual character of titanium in carbon alloys. At a titanium content of up to 0.1–0.2 wt.% the content of cementite in solid solution grains decreases, which results in a drop of the H_μ^a and HV values. And at a higher content of titanium, it behaves as a carbide-forming element, thus leading to increase in hardness of the deposited metal.

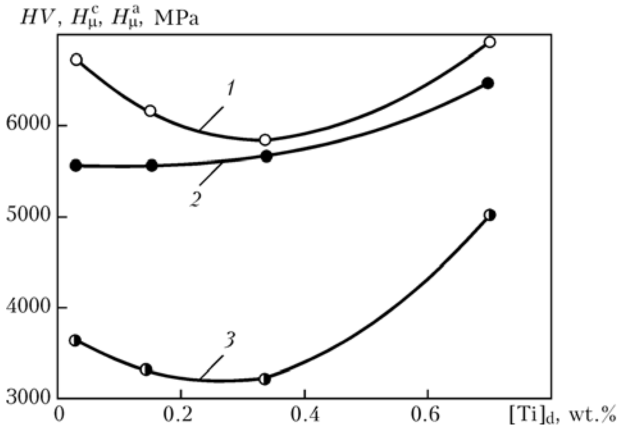

Figure 2. Effect of titanium on hardness of deposited metal (*1*), microhardness of carbide-cementite network (*2*) and solid solution grains (*3*)

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NEWS

VERSATILE SEMI-AUTOMATIC WELDING DEVICE OF THE LIMITED LIABILITY COMPANY «ShTORM-ITS»

In 2007, the Limited Liability Company «Shtorm ITS» has completed the work on a new model of semi-automatic welding device PDGO-528 M, which combines reliability, functionality, easy control and affordable price. This model is designed for welding of parts from low-carbon, low-alloy and alloyed steels, aluminium and copper. Welding can be performed with continuous or intermittent welds by using steel (0.8–1.6 mm diameter), aluminium (1.2–2.0 mm diameter) or flux-cored (1.0–3.2 mm diameter) wires.

The semi-automatic welding device can operate with different welding rectifiers at a current of 60 to 500 A. The device is designed on the basis of a 4-roller wire feed mechanism, which provides a stable feed of the wire and causes no difficulties in its passing via the torch channel independently of the quality of winding on a spool and oscillations of voltage in the supply circuit. The device is available in two modifications: with gas or fluid cooling of the torch. The welding head can be quickly connected to the semi-automatic welding device using a central European-type connector. Owing to separately regulated pressing of the wire and high torque, the device generates a substantial wire pushing force, which makes it possible to use welding torches with a hose up to 5 m long.

New control board is built into the device casing. This model of the device realises the following functions: protection of engine from overloading, protection of control circuit from welding voltage, and protection of power transistors from overheating.

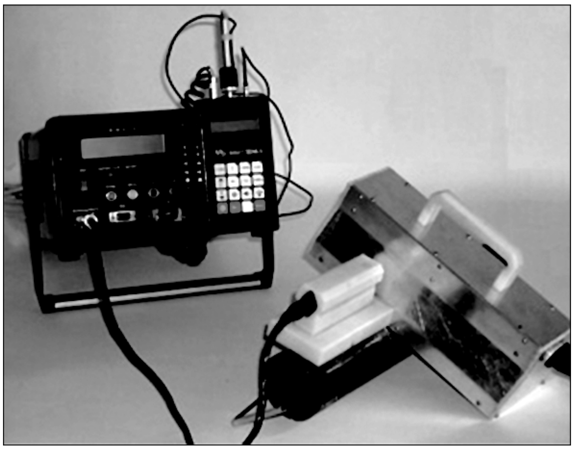
Versatile powering of the control circuit makes it possible to utilise a wide range of supply voltages.

The device is provided with a possibility of setting the time of gas purging before and after welding, as well as the minimal and maximal value of the wire feed rate during welding. The maximal length of the package that does not lead to a loss of functional capabilities of the semi-automatic device is 50 m. The device is compact, light-weight (17 kg), and has a modern and ergonomic design: a flap lid of the device allows quick replacement of the rollers, and a special handle makes it possible to easily move it over the territory of a workshop. The reinforced casing of the device allows using it under intensive production conditions.

Physically, the semi-automatic device is equipped with a wire spool holder, the spool having a diameter of 300 mm (European standard), weight of up to 18 kg, and plastic jacket protecting the wire from contamination. The semi-automatic device can be delivered without a jacket, which makes the model purchased less expensive and simplifies the process of replacement of the wire.

PDGO-528 M is repairable and easy to maintain, comprising no hard-to-replace mechanisms. It is provided with warranty (1 year) and post-warranty service, and with sealed components.

DEVICE FMKh-1 FOR EVALUATION OF PHYSICAL-MECHANICAL CHARACTERISTICS OF STEELS



Ivano-Frankovsk National Technical University, Ukraine, has developed a portable device FMKh-1 for evaluation of physical-mechanical characteristics of steels. The device can be used to evaluate yield stress (in a range of 200–800 MPa) and tensile strength (in a range of 400–1000 MPa) of materials at an error of not more than 10 %. Mechanical characteristics are evaluated on the basis of their dependence upon the hardness and thermal conductivity of a material. The integrated algorithm of processing the measurement information is based on neuron networks. The device has the possibility of determining steel structure, and can operate in the PC controlled or independent mode. The specialised software has been developed to synchronise the device with PC.

2nd SCIENTIFIC-PRACTICAL CONFERENCE AT OJSC «SELMA FIRM»

The 2nd Scientific-Practical Conference «Quality Assurance in Welding Production. Welding Equipment and Consumables. Standards. Personnel» organized by Ukrainian Welders Society Council and Crimean Regional Division of Ukrainian Welders Society was held at «SELMA Firm» Simferopol Electric Machine Building Plant on June 7--8, 2007. More than 50 specialists of welding production from 15 regions of Ukraine participated in its work.

When opening the Conference, V.G. Fartushny, President of Ukrainian Welders Society, read the welcome address of academician B.E. Paton, PWI Director, to its participants, noting the urgency and importance of Conference subjects, and expressing the wishes of successful work.

Yu.V. Butenko, a member of Ukrainian Welders Society Council, Chairman of the Commission on Quality Problems, Chief Welder of PA «Zorya-Mashproekt» addressed the Conference with the report on «Problems of Quality Assurance in Welding Production». Analyzing the status of welding production in major machine-building enterprises, the speaker noted that under current conditions the factors determining the quality and, consequently, competitive ability of a welded structure are not only the quality of welding consumables and equipment, but also staff qualifications (workers, technical and engineering employees, welding operation supervisors), welding operation organization (including the availability of upgraded standards), and modern technological process (sequence of the technological operations, availability of operation-by-operation inspection, product certification). At present the most critical problem is that of staffing the industry with qualified welders-workers skilled in modern technologies of welding, surfacing, cutting and able to correctly select the required consumables and equipment. Unfortunately, the currently available training of welders-workers in the system of professional training does not meet the production demands. The problems of professional training are well known: poor material and technical facilities, low salaries of the teaching staff, lack of possibility for students to get practical training on modern equipment, absence of programs and procedures of welders training, corresponding to international standards. The enterprise is forced to organize additional courses in-house for providing qualified personnel for welding production, but this does not solve the problem, as the plant system of training is also far from perfect. In Ukraine the system of welders-workers training for different specialties is already successfully realized in PWI Interindustry Training-Attestation Center. However, this Center is the only one, and it cannot solve the problem for all the Ukrainian welding production. At present the efforts of Ukrainian Welders Society together with interested ministries and departments should be focused on creation of regional centers for qualified worker training, fitted with modern welding equipment and meeting the requirements of welding production. Over the last years the lack of qualified technical and engineering employees has been also found. Unfortunately, the chairs of welding in high educational institutions are not able to meet the demands of modern production. Graduates of high education institutes do not have sufficient knowledge of the modern welding equipment, the status of international standards and norms, and have limited practical experience. In the previous years a young welding engineer, employed by the chief welder service of a mechanical engineering plant, was able, using the principle of «generation succession», to acquire the appropriate technical skills. At present, however, when the number of staff in the chief welder service is minimized, a young specialist is required «to joint the battle» at once, but a lack of proper training does not enable him to do this. It is necessary to essentially revise the system of welding engineer training in the higher education institutes to include a study of international standards and norms into the program. Yu.V. Butenko also drew the attention of Conference participants to problems now facing a plant's chief welder, the main of which is the absence of legislatively defined rights of welding operation supervisor. Under the current conditions, the full responsibility for welding construction reliability lies on the chief welder; however, he does not have the right to take decisions. Here is the simplest example: the purchase of consumables, base metal and welding equipment for welded structure fabrication is completely done by the supply agent, who is guided not

by the technical necessity, but by price. The availability of quality certificate and certificate of compliance does not always guarantee that welding equipment corresponds to the requirements of concrete production and production conditions of concrete welding structure. Participation of the chief welder, specialists from chief welder's service in the selection and purchase of materials and equipment is obligatory. It is time to work out and to appropriately confirm the Provisions (Technical Regulations) on the chief welder service. The members of the Ukrainian Welders Society should take an active part in its preparation, based on cumulative experience and currently valid international norms and standards. It should specify the rights and duties of welding operations supervisor and his services, the service status within the administration structure of the enterprise. Yu.V. Butenko further discussed the problem of welding consumables and equipment quality. At present the supply of welding equipment in the Ukrainian market exceeds the demand. However, by any means, not all the proposed welding equipment has the required operating parameters. It is very difficult to choose the required consumable or equipment. When choosing welding equipment, the buyers are mostly guided by the experience of its operation, as well as manufacturer or supplier reputation. The Ukrainian Welders Society should create the data base of the experience of application of different welding equipment at the enterprises of all branches of industry that could allow taking unbiased decisions when choosing the welding equipment, and could limit the access of unscrupulous manufacturer and supplier products to the market.

The report of *N.A. Protsenko*, Manager of the European Welding Federation Scheme, UNOSP «PatonCert», «System of Enterprises Preparation to Certification to the Requirements of ISO 3834 International Standard» was devoted, in particular, to one of the currently important problems — providing the local welding production with modern standard-technical documentation (primarily, standards that meet the requirements of international codes). N.A. Protsenko, continuing the discussion of the problems of providing the welding production with scientific-technical documentation, that was started in Yu.V. Butenko's presentation, noted that in the majority of leading branches of industry, manufacturing and operating the most critical welded structures (heavy and transportation mechanical engineering, power generation, power and chemical engineering, pipeline system operation, etc.) the old state (interstate) and branch standards of former USSR, written more than 25 years ago, are still valid without any changes introduced. The majority of these documents were revised in Russia and new GOST R and Federal Codes were compiled, accounting for the changes occurring in the world welding production for the last years. System work on creation of standards, harmonized with international EN and ISO standards was started in Ukraine. It is necessary to harmonize about 240 standards to satisfy the demands of the local welding production. Leading research organizations and industrial enterprises of Ukraine are involved in this task realization. However, as usual, this work does not have purpose funding and is based mainly on the enthusiasm of specialists, who understand all the importance of creation of modern standards which should ensure the quality and competitive ability of welded structures. The first DSTU ISO standards in the field of welding consumables, shielding gases and so on were introduced in 2004–2006. ISO 3834 is the «main» standard of welding production for improvement of the system of welding operation organization and the possibility of welding production certification. Introduction of this standard permits step-by-step realization of the process of welding operation organization and performance that includes the requirements to contract preparation and selection of subcontractor organizations, qualification of managing and executive personnel, selection of welding equipment, as well as the base and consumable materials, to preparation, formalization and certification of technical processes, in-process inspection, final control of product quality and acceptance tests, control of deviations from the technological process, documenting the results of work performance, identification and traceability of technological operation performance. Authorized National Body on welding production certification — UNOSP «PatonCert» was set up at PWI for confirmation of welding production compliance to ISO 3834 requirements. «PatonCert» successfully passed accreditation in European Welding Federation and obtained the appropriate certificate in June 2006.

Over the last 20 years technical progress in welding production has been achieved through realization of the provisions of ISO 9000 series international standards. The validity term of the third version of the mentioned standards will be over in 2008. The presentation of *A.E. Marchenko* (PWI) «Improvement of Quality Management Taking into Consideration the International Standard Provisions» was devoted to possible changes in ISO 9000 standards. It is anticipated that ISO 9001 standard will remain to be the main document that regulates the demands to quality management system (QMS), and it will be used for evaluation of QMS effectiveness in the process of its certification. The main purpose of QMS developed and certified in accordance with 9001 ISO, is to provide compliance of product quality to the demands stated by the manufacturer or specified (anticipated) by the customer or society. In 2008 the ISO 9001 standard version will be slightly changed. With the aim to achieve the highest economical results of enterprises activity, ISO 9004 standard will be oriented, as before, towards improvement of general management, a constituent part of which is quality management. Considering that over the last period this problem was solved unsatisfactorily, ISO / TK178 planned an essential revision of ISO 9004 by 2008. The new version of ISO 9004 standard is aimed at achievement of sustainable enterprise development. When working out ISO 9004 standard, the approaches, successfully realized in Japanese standards JIS / TR Q 0005 «Systems for quality management. Guiding principles for sustainable growth», JIS / TR Q 0006 «Systems for quality management. Guidelines for self-rating», draft of French standard «Management system. Guiding principles for organization management», Spanish standard «Methods and plans for improvement», and European model of business perfection (EFQM), Malcolm Boldridge and Edward Deming bonus models, were suggested as examples. These suggestions should be thoroughly analyzed by welders-specialists and welding equipment manufacturers. The ways for ISO 3834 standard harmonization with the structure of the new version of ISO 9001:2008 standard should be found. At present such harmonization does not exist and that creates difficulties in development and certification of welding processes on the one hand and certification of quality management systems with application of welding technologies on the other hand.

Modern welding production makes special demands of professional training in welding production. The report by P.P. Protsenko, Director of PWI Interindustry Training-Attestation Center, on «Personnel Professional Qualification as the Determinant Factor in the System of Quality Assurance of Welded Structures» was devoted to new approaches in professional training organization for all categories of personnel (from welding operation supervisor to a welder). The reporter noted that in order to solve the problem of professional personnel training the International Institute of Welding and the European Welding Federation worked out the common training programs and system of monitoring for conducting qualification examinations, corresponding to ISO 3834 requirements. International qualification system IIW-ESF is recognized by all accreditation authorities in the world and allows guaranteeing the level of training and evaluation of personnel qualification irrespective of the country, in which the personnel were trained and certified. Authorized National Bodies (ANB) in 35 countries, including Ukraine, obtained accreditation for application of the International Qualification System. PWI ITAC was accredited as ANB in Ukraine. In the process of preparation to accreditation, programs and procedures were developed for evaluation of training and qualification for all personnel categories in welding industry that permitted organizing training and certification of international class specialists. Participation of such specialists is obligatory in fabrication of welded structures, satisfying the requirements of ISO 3834. And while no problems were encountered when developing and coordinating the Program and Directive on confirmation of international qualification of engineering and technical personnel, difficulties arose when coordinating the system of welders training. This is connected, to a greater extent, with inconsistency between the national system of professional and technical training of workers and the guiding documents of the International Qualification System. Under the current situation it is necessary to develop the Provisions and create a multilevel system of continuous professional training for different categories of personnel in order to solve the problem of providing welding production with qualified personnel. Regional resource centers on welding and allied technologies, established with the participation of the Ukrainian Welders Society, Authorized National Body on international personnel qualification, interested ministries and industrial enterprises of Ukraine, could be a training-production base for training highly qualified personnel.

G.V. Pavlenko, Chairman of the Crimean Regional Division of UWS, General Director of OJSC «Selma Firm» (Simferopol); V.I. Degtyar, Chairman of the Odessa UWS Regional Division (Odessa); M.A. Laktionov, Chairman of Sumy USW Regional Division; V.T. Kotik, Director of UAKS; V.M. Ilyushenko, Vice-President of USW (Kiev) participated in the discussion on urgent problems of improving the quality of welding operations discussed at the Conference.

By the results of discussions a decision was taken, including a commission to the Ukrainian Welders Society, to work out the draft of the Provisions on the chief welder, taking into consideration the international standards, prepare Provisions on the welding production resource centers for training welders-workers with qualification meeting the requirements of the international standards and modern production.

The District and Regional Divisions of the Ukrainian Welders Society were entrusted to organize with the assistance of Welders Society Council the monitoring of welding consumables and equipment compliance to the requirements of standard documentation and technology of manufacturing a specific welded structure, create a data base of the experience of operating the welding equipment used at the enterprises of Ukraine.

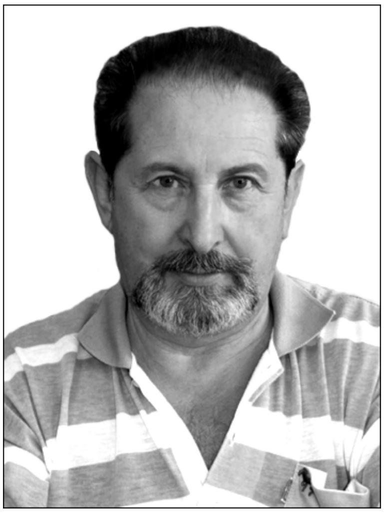
In 2008 it is planned to hold a Scientific-Practical Conference on the problems of quality assurance in welding production.

All the participants were able to become familiarized with the modern production of welding equipment at OJSC «Simferopol Machine-Building Plant «SELMA Firm» during the work of the Conference. At present the production shops of the plant are fitted with the most modern technological equipment permitting manufacture of welding and special equipment, reliable in operation, for manual, mechanized and automatic arc welding, argon-arc welding and air-plasma cutting, machines for edge preparation, units for resistance welding. «SELMA Firm» products are successfully operating at Ukrainian plants, and are exported to many countries.

Active marketing policy, permanent contacts with the scientific centers of Ukraine and Russia permit the Company to develop and master in the shortest time the manufacturing of new and modified samples of welding equipment, meeting the requirements of international standards and welding equipment users.

B.V. Yurlov, V.M. Ilyushenko,
Cand. of Sci. (Eng.), PWI

OUR CONGRATULATIONS!



Vladimir L. Najda, talented designer, Corresponding Member of the Academy of Engineering Sciences of Ukraine, and Head of Department for automated NDT means at the Design Bureau of the E.O. Paton Electric Welding Institute, celebrates his 70th birthday this October.

V.L. Najda was born in Dnepropetrovsk. He graduated in 1965 from the Moscow Energy Institute in speciality «Electrification of Industrial Enterprises and Plants». He joined the Design Bureau of the E.O. Paton Electric Welding Institute in 1972, being a mature specialist in the field of automatic systems for control of equipment. The first control systems based on contactless electronic elements, which he developed, are utilised in automatic machine tools and automatic lines for cladding car engine valves, and are applied to advantage at AutoVAZ, KamAZ, ZIL and other factories.

In 1984 he became the Head of Department for automated NDT means. Automated systems for ultrasonic inspection of various parts were developed and successfully applied under his direct supervision at the «Yuzhmash» Plant (Dnepropetrovsk), at the Vyksunsky Metallurgical Works and other enterprises.

Systems for NDT of welds and metal structures employed at nuclear power plants in Russia and Ukraine have been domestically built in the last years. This equipment substitutes for manual inspection of environmentally hazardous facilities using computerised diagnostics, and successfully competes with imported equipment by supporting safety of nuclear power generation facilities and extending life of their components. The latest developments profitably employed at the nuclear power plants in Russia and Ukraine include systems of the NK293, NK300 and NK321 types for ultrasonic inspection of the first loop objects, manipulator NK331 and probes VSZ-10.8 for eddy current inspection of heat-exchanging pipes and bridges of steam generator collectors for reactors WWER-1000.

Successful activities of the Department headed by V.L. Najda in the field of non-destructive testing allowed it to win in 2004–2005 a critical-importance order from the Vyksunsky Metallurgical Works — to manufacture systems for ultrasonic inspection of welds and end regions of pipes with a diameter of 508–1420 mm and wall thickness of 7–50 mm. As a result of the two-stage bid, the order was won by the V.L. Najda's team. By now, six systems NK360, NK361 and NK362 have been accepted by the customer and applied with profit. According to the level of automation and computer programming, this project accomplished within the extremely short terms, which combines the most advanced elements of mechanics and electronics, laser and ultrasonic equipment, undoubtedly belongs to engineering of the 21st century. At present, the team headed by V.L. Najda is performing the order it won at an international bid to develop and manufacture two systems for automated ultrasonic inspection of railway wheels, and another two systems for inspection of end regions of pipes. V.L. Najda is an author of 93 scientific publications, including one book and 38 author's certificates and patents.

Mikhail F. Gnatenko, Director General of the Limited Liability Company «Velma» is 60 this October.

After graduating in 1972 from the Kiev Polytechnic Institute, he was working at the Cherepovets Steel Rolling Works, where he took an active part in development and improvement of the technology for manufacture of welding electrodes.

In 1977, M.F. Gnatenko joined the post-graduate courses, and after finishing them he continued his scientific work at the E.O. Paton Electric Welding Institute. In 1984, M.F. Gnatenko successfully defended his thesis for a candidate of technical sciences degree. While working at the Institute (till 1992), he made a great contribution to the development of low-toxicity electrodes, advanced technological processes of conveyer production of electrodes, development and upgrading of basic process equipment (carbon extrusion presses, furnaces for heat treatment of electrodes, intensive mixing machines, batch measuring lines, etc.).

In 1993, M.F. Gnatenko joined the Limited Liability Company «Velma» to work as a technical director, and since 2005 up to now he has been working as the Director General.

Owing to the persistence and engineering talent of M.F. Gnatenko, «Velma» developed and introduced into production the fourth generation of the process equipment for manufacture of electrodes, and did a big job on improvement of the technological processes. More than 60 pieces of equipment and about 30 production lines for manufacture of welding electrodes were supplied to such manufacturers of welding electrodes as Closed Joint Stock Company «Artem-mash-Vistek», Open Joint Stock Company «Dneprometiz», Pilot Plant for Welding Consumables of the E.O. Paton Electric Welding Institute, Limited Liability Company «Plazma Tekh», Open Joint Stock Company «Losinoostrovsky Electrode Factory», Open Joint Stock Company «Mezhgos-metiz-Mtsensk», Open Joint Stock Company «Uralvagonzavod», etc.

Our sincere congratulations to the above persons celebrating their jubilees, and our best wishes to them for good health, much happiness and continued success!

E.O. Paton Electric Welding Institute
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