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OPTIMIZATION OF THE MECHANISM WELDING MODE IN A SHIELDING GASES ENVIRONMENT OF SHELL STRUCTURES IN THE POSITION "ON WEIGHT"

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Abstract. Due to their simplified spatial shape, shell cylindrical designs have acceptable manufacturability. The latter makes it possible to use a variety of fusion welding methods in their manufacture, including the option of mechanized welding in protective gas environments. Such a technological process is considered to be sufficiently developed in terms of theory and application, as evidenced by specialized equipment for it and numerous recommendations for the selection of installation and running welding parameters. Analysis of such material demonstrates that the basic technology is welding in the lower position with a seam root lining or with the use of a suitable technological arrangement for rotating large structures to provide such conditions. Much more difficult to meet the quality requirements for a welded joint are repair and welding works of non-rotating structures with a one-sided approach to the welding zone and the absence of a seam root lining.

In this case, welding equipment with electric or electric-mechanical control of the process of dropwise transfer of metal into the bath is used, regardless of the spatial position of the seam. However, in cases of single production or repair welding, classical welding sources are still widely used, in which the regulatory requirements for the weld are provided by its appropriate external characteristics, the effect of self-regulation of the arc and dynamic characteristics. Here, the variant of droplet transfer with a short circuit of the droplet to the bath is typical, with the characteristic instability of energy accumulation / return of the source choke at the stages of the arc and droplet and the corresponding behavior of the arc in different spatial positions.

Since the parameters of the mode are interdependent and, thus, welding itself represents a poorly organized system that has a variety of physical parameters that cause different in nature, but tightly interconnected processes in the zone of weld formation. The best tool for assessing the condition and regulation of such a system today is planning an experiment with independent controlled (setting) parameters of the welding mode and quality feedback – the optimized amount of weld penetration. On the basis of the processing of the array of recommended data regarding the selection of the value of the setting parameters of the welding process by the procedure of constructing symmetric histograms and the distribution polygon and calculating the analytical model of the description of the distribution density for each setting parameter of the process, their average values are set with a probability of 0.9. The latter were used to calculate the actual values of the following parameters for welding a given material thickness – electrode wire diameter 1.6 mm, welding current 190 A, voltage 25±1 V, welding speed – 26–42 m/h, wire feed speed 21–29 m/h, electrode discharge wire 16 mm. On the basis of the specified reference base of parameter values, a planned experiment was set up and implemented to find the optimum on a matrix of a composite symmetrical three-level plan, as variable factors are set – process voltage, welding wire feed speed and welding speed; the height of penetration of the assembled parts is set by the response. The region of the optimum and the influence of the setting parameters of the mode on it, as well as the analysis of its response surfaces and cross sections of such surfaces demonstrate that the setting parameter – the source voltage should practically be constant at the level of 24 V and does not have a significant adjustment ability for the correction of the welding mode. The setting kinematic parameters of the mode are the wire feed speed and the welding speed, respectively 23 and 27 m/h, at the given arc voltage, they provide welding in one pass. In terms of the depth of the ability to adjust the quality of the seam formation, the welding speed prevails, since, all other things being equal, the wire feed speed is strictly correlated with the speed of its melting at a given diameter and electrode distance. The latter determine the actual value of the current, the value of which is limited by the source voltage, which is strictly specified and constant for the given process under study.

Keywords: mechanized welding, shielding gases, parameters of the welding mode, spatial position of the welding zone, drop transfer of metal, adjustment of the welding mode, statistical methods of evaluation of the mode parameters, optimization of the setting parameters of the mode

Introduction and Problem Statement

Shell elements are widely used in various industries. The simplified spatial form is technological enough to be used in their manufacture for various welding methods, in particular, mechanized and automated arc welding with a fusible electrode wire in various protective, including gas, environments.

Here, the formation of a dense, strong seam with the specified normative geometric dimensions is ensured by the transfer of drops of molten metal of the electrode wire through the gas-protected arc gap into the welding bath.

In case of mass or serial production, it is advisable to use modern synergistic sources in combination with a developed technological arrangement to control the quality consequences of such a process. The former program and strictly monitor the dynamics of the current parameters of the weld seam formation mode, and the latter provide welding conditions in the lower position (if product rotation is possible) on the substrate for guaranteed penetration of the seam root. Such sources use the principles of dynamic electrical and mechanical-electrical stabilization of processes in the arc gap [1, 2], and in the technological arrangement, for example, monitoring of the welding bath . However, in conditions of single production, as well as repair or restoration of shell structures, classical welding sources with independent or coordinated with the electrical parameters of the mode wire feeding systems are still widely used. The simplest of them are structurally based on stepwise adjustment of both electrical and mechanical setting parameters of the mode [3]. The technological setting in the conditions of “field repair” is simplified, and the impossibility of turning the repair product for welding in the standard lower position in the absence of access to the back surface of the seam execution zone objectively requires welding “on a weight” in a different spatial position with the strict need to achieve the given shape of the seam root [4, 5].

Practical approaches in such conditions, to achieve stable welding quality indicators, are to use the effect of self-adjustment of the arc gap and to switch to a multilayer seam, in order to avoid excessive penetration or cutting of the seam root [7, 8].

Here, the most typical is the transfer of the drop during the short circuit of the arc gap. Drops of metal from the end of the electrode with a certain periodicity either change the length of the arc or close the electrode gap for a certain time in the intervals: 50–10 ms at the stage of drop formation and 1...10ms at the stage of closing the drop with the bath mirror.

Such processes are correctly described by the superposition of mechanical, electrical, and gas-dynamic forces, the influence of which on the development and type of drop transfer, all other things being equal, also depends on the spatial position of the arc gap [5–8].

Production losses due to splashing, metal burnout, etc. can be minimized by forced short-circuiting of the drop on the bath, which requires a rigid, positively decreasing or universal external characteristic of the source and ensuring its high dynamics (high speed of short-circuit current growth at low values of arc voltage) [5–9].

The setting parameters of the mechanized welding mode in the environment of shielding gases are set due to the regulatory requirements for the geometry of the seam for the product made of this material and its thickness, due to the optimal value of the thermal energy of the arc process per unit length of the seam taking into account the formation of the desired structure of the welding zone [10].

An integral indicator of this is the continuous welding energy, which by its value connects the electrical, mechanical, geometric, etc. current parameters of the regime with the given parameters of the gas protection of the arc zone [9, 10].

Accordingly, the running parameters of the regime are interdependent and, thus, the welding itself represents a poorly organized system that has various physical parameters that cause different in nature, but closely related processes in the zone of weld formation. The best methodological tool for assessing the condition and regulation of such a system today is planning an experiment with independent controlled (setting) parameters of the welding mode [11–14].

The purpose of the work is to optimize the amount of weld penetration (reliability Q=0.95) of a given geometry in the variant of single-layer and multi-layer filling of the joint during mechanized welding in a shielding gas environment of non-rotating joints of the shell structure in the variant of execution of the root of the seam "on weight" on classic welding equipment with reliable (Q≥0.9) by determining the current and setting parameters of the process.

In the course of the work, the following tasks must be solved: 1) Establishing an integral indicator of the optimality of the technological process of repair welding, which clearly affects the value of the current parameters of the process and the final structure of the metal of the welding zone; 2. Identification of statistically significant values of setting and running parameters of the process of mechanized welding in the environment of protective gases; 3. Conducting a planned technological experiment to establish the optimal values of the setting parameters of the process.

Review of Modern Information Sources on the Subject of the Paper

At the present day of Denmark, the technological process is sufficiently theoretically primed, practically implemented and widely developed [4, 5, 7].

An indicator of the thoroughness and quality of the process of mechanized welding in the medium of sour gases is the correlation of geometric and energy parameters [10], and the penetration depth itself h_d (mm) and the heat input of welding q_{de} (cal·s/m).

$$h_d = 2\sqrt{\frac{q_{de}}{\pi \cdot e \cdot c \cdot \gamma \cdot T_m \cdot \phi_P}}, \tag{1}$$

where $q_{de} = \frac{0.24 \cdot I_W \cdot U_a \cdot \eta}{v_W}$; e – width of seam reinforcement; c – height of a single surfacing layer; γ – specific weight of the metal; T_m – melting point; ϕ_P – coefficient of the form of boiling; I_W- quarrel current; U_a – arc voltage drop; v_W – welding speed; η – coefficient of performance.

From (1) follows a complete description of mutual relationships and dependencies between kinematic, energy and geometric running parameters of the process, which allows both the selection of their values, as well as software and corrective monitoring of such parameters when using specialized equipment [3, 5, 14].

However, it should be noted that the recommendations for the selection of parameters are mainly focused on standard welding in the lower position with a seam root lining and have a significant range of values. They practically lack information about certain electrical characteristics of the used sources, in particular the inductance, which causes the inertia of the dynamic external characteristics of the source and transient processes in the welding zone.

Their generalization (Figs. 1–3) by indicators of process efficiency (coefficients of losses, surfacing, melting) is described by comb functions, the poles of which show a strict dependence on certain setting or running parameters of the process. The latter requires a strict reference to them when calculating the welding mode, and also indicates the objective need to take into account the mechanism of drop formation, its transfer to the metal of the bath, the mass of metal transferred from the electrode wire, the spatial position of the arc discharge, etc.

In the absence of feedback between the setting electrical and mechanical parameters of the mechanized welding mode (independent wire feed speed), sufficient production indicators (coefficients of melting, surfacing, burnout losses, seam shapes, etc.) can be provided, to a certain extent, by the developed effect of self-adjustment of the arc and high dynamic and energy indicators of the source. The latter requires an instantaneous change in the inductive power of the source choke to restore the burning of the arc accumulated during the short-circuit interval of the drop to the bath.

By changing the values of the set of setting parameters of the mode, while preserving the basic requirements for stable drop transfer, all types of drop transfer from the end of the electrode wire to the welding bath can be achieved.

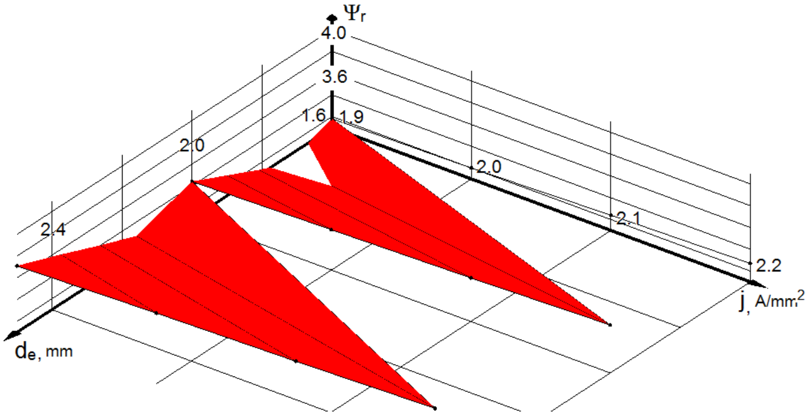


Fig. 1. The response surface of the dependence
of the electrode metal loss coefficient on burnout and spattering *Ψr* on the diameter
of the electrode wire *de* and the current density *j* in it

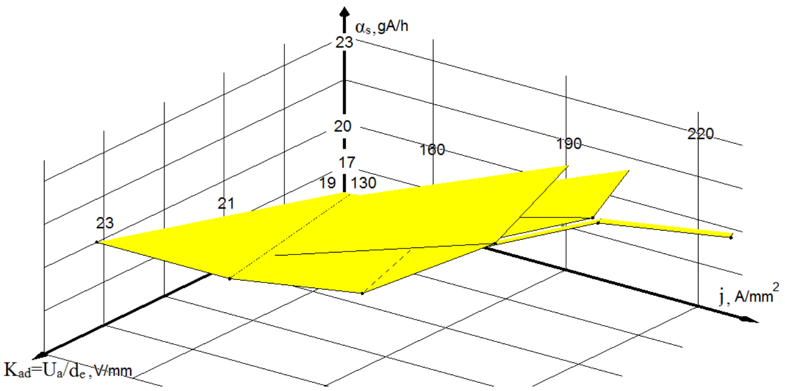


Fig. 2. The response surface of the dependence
of the electrode metal melting coefficient α_s on the K_{ad} -coefficient is the ratio
of the voltage on the arc U_a to the diameter of the electrode wire d_e and the current density *j* in it

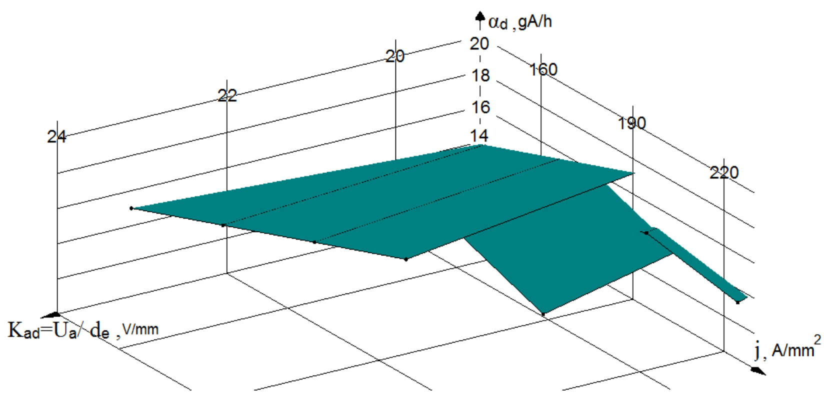
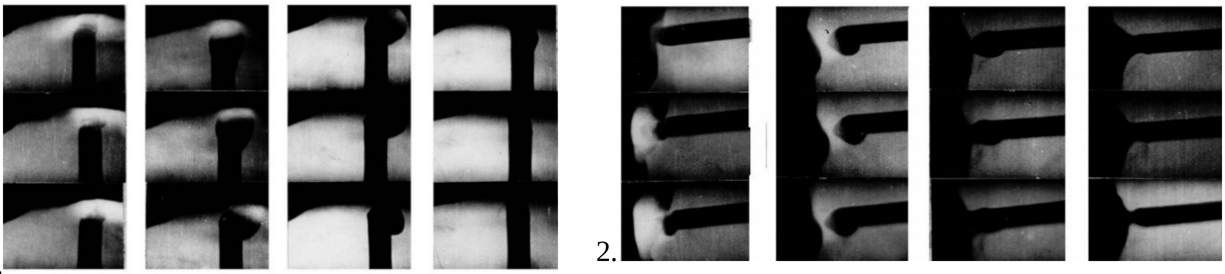


Fig. 3. The response surface of the dependence
of the electrode metal deposition coefficient α_d on the K_{ad} -coefficient is the ratio
of the voltage on the arc U_a to the diameter of the electrode wire d_e and the current density *j* in it

It is possible to stabilize the droplet transfer in the most common option – the droplet transfer during the short-circuit of the arc interval can be forced, for example, using STT-, SMT-technologies [1, 2], and when using classical sources with hard, positively decreasing external characteristics, provided that the arc power in the interval changes instantaneously burning and short-circuit intervals and the presence of a self-regulating effect.

The burning time of the arc depends on the energy accumulated in the choke of the welding source in the short-circuit cycle at a given value of the welding current. Since their time intervals are variable, accordingly, such energy also fluctuates within certain limits. Then the penetration depth has a probabilistic character.



1. 2.

Fig. 4. Cinematographic image of the mechanized welding process in a carbon dioxide environment: 1 – vertical position; 2 – ceiling position [5]

An additional unfavorable factor affecting the conditions of seam formation is the movement of the metal of the bath in different spatial welding positions, especially with the reverse polarity of the source connection due to the unstable spatial orientation of the arc (Fig. 4).

A certain stabilizing parameter in this case, all other things being equal, is the use of a mixture of shielding gases. If the final structure of the metal of the welding zone allows the use of oxygen shielding gases in the composition, then the latter, thanks to its physical and chemical properties, provides the desired option of droplet transfer (smaller drops) with a certain energy stabilization of the process (increasing current density in a reduced cross-section of the arc column) and spatial orientation arcs (stiffness of the column).

Main Material Presentation

The basis for optimizing the welding process is to ensure the physical weldability of the material and the standard quality of the seam:

1. The heating rate vn to a temperature of 900 °C at the level of 1200 °C/s, the cooling speed $V_{o/900}$ at a temperature of 900 °C should be 120 $^{\circ}$/s, the cooling speed $v_{0/550}$ from temperature of 550 °C is taken as 38 °C;

2. Time intervals of the thermal cycle: the heating time tn in the temperature range above 900 °C is 0.6s, the cooling time t_0 from the temperature of 900 °C is taken as 18 s;

3. The unit penetration depth (1) depends on the spatial position of the seam repair area;

4. The stability of the droplet transfer process, other things being equal, is determined by the equality of the wire feeding speed and its melting speed.

Then the energy-kinetic condition (the value of the linear welding energy q/v) for setting the optimized values of the setting and running parameters is

$$\frac{q_{de}}{v} = \delta\sqrt{\frac{2\cdot\pi\cdot\lambda\cdot c\gamma(T-T_0)^2}{v_0}} = 798\ldots2437 \text{ cal/cm}, \qquad (2)$$

where δ = 0.4 cm – sheet thickness; λ = 0.1 cal/cm °C·s– thermal conductivity; $c\gamma$ = 1.25 cal/cm$^{3\cdot}$ °C – specific heat capacity; v_0 = 0.12–7 °C/s – the optimal range of the cooling rate in the temperature interval T=550° – the temperature of the minimum resistance of austenite, T =20°.

The set of setting parameters consists of:

1. Fully controlled – they allow their change in value within the limits of the depth of adjustment of the device that provides them and the conditions for the formation of the standard seam according to the geometric characteristics and have a numerical calculation (current strength *Iw*, voltage of the welding zone *Ua*, welding speed *Vs*, wire feed speed *Vfs*, shielding gas consumption Q);

2. Conditionally controlled – selected and fixed over the entire welding mode adjustment range, based on the conditions for meeting the mechanical and chemical properties of the weld metal – the diameter of the electrode wire *de*, the length of the wire *le*, the assembly gap Δ between the parts or the edge cutting angle *γ*, the number of passes *n* required and sufficient to fill the given cross-section of the seam, the composition of gas protection.

There is a connection between controlled and conditionally controlled parameters due to a complex of processes that occur under welding conditions, and the deviation of which ultimately leads to the formation of product defects. A large number of recommendations regarding the value of the setting parameters with a wide range of their values [5–8, 14] requires setting their most statistically significant value before applying the calculation form. For this, the procedure of the non-parametric method of estimating the average of the 5 estimates of the ensemble of data [15] and its description by a continuous analytical model (reliable probability $P_{0.9}$ of Table 1, Figs. 5–7) was chosen.

1. Estimate of the average for *n* values $\bar{x} = \frac{\sum_1^n x_i}{n}$, where x_i is the value of the setting parameter from the *n* array of its recommended values.

2. Estimation of the median x_{med} – 50 % quantile of the distribution.

3 Estimation of the range $x_p = (x_{imax} - x_{jmin})/2$, where x_{imax},x_{jmin} – the corresponding maximum and minimum value of the parameter in its variation series.

4. Estimation of the average by quartiles of a symmetrical distribution $x_{\kappa в} = \frac{x_{0.5}+x_{0.75}}{2}$, where $x_{0.25}$ and $x_{0.75}$ correspond to the value of the parameter, respectively, 25 % and 75 % of the array of its data grouped in the variation series.

5. Estimate of the strongly cut average $x_{50\,\%}$ – the number of values of the parameter between the quartiles $x_{0.25}$ and $x_{0.75}$, $x_{50\,\%} = \frac{\sum x_k - (\sum x_{0.25} + x_{0.75})}{n/2}$, where Σx_K is the total number of parameter value values in the variation series of size n, $\Sigma x_{0.25}$, Σx_{075} is the number of parameter value values belonging to the 25 % and 75 % quartiles.

Table 1

Calculation of the most probable value (P=0.9) of the setting parameter of the welding mode

Setting parameters of the welding mode	Estimates of the average variation series					The average of 5 grades in a row	$2n_B$	σ_{xi}	$\sigma_{\bar{x}}$	$\pm\Delta_{0.9\bar{x}}$	Parameter value
	$\bar{x}$	x_{med}	x_p	x_{kv}	$x_{50\%}$						
I_w	205	185	185	190	202	190	0.3	6.875	35.3	57	190 A
U_a	24	23	24	23.5	21	23.5	0.4	8.125	2.3	3.6	23.5 V
d_e	1.9	2.0	2.3	1.6	1.6	1.9	0.1	1.17	0.37	0.6	2.0 mm
V_w	24	25	28	26	23	24	0	6.4	2.26	3.6	25 m/h

For technical systems, most polygons of their distribution can be represented by an analytical description in the form of models belonging to the class of exponential types (Figs. 5–7)

$$p(x) = A \cdot exp(-\left|\frac{x}{\lambda\sigma}\right|^{\alpha}), \quad (3)$$

where *A*, *α* , $\lambda\sigma = X_0$ are distribution parameters.

1. Parameter *A* at any value $X_0 \neq 0$ is simply equal to the value of the function *p(x)*, if x= 0; X_0 – scale factor.

2. Parameter α is calculated in the form $= \frac{\Delta\, ln\left[-ln\frac{p(x)}{A}\right]}{\Delta\, ln\, x}$.

3. Parameter X_0 (scale factor) is determined from relation $-\frac{ln\, p(x)}{A} = \left|\frac{x}{X_0}\right|^{\alpha}$.

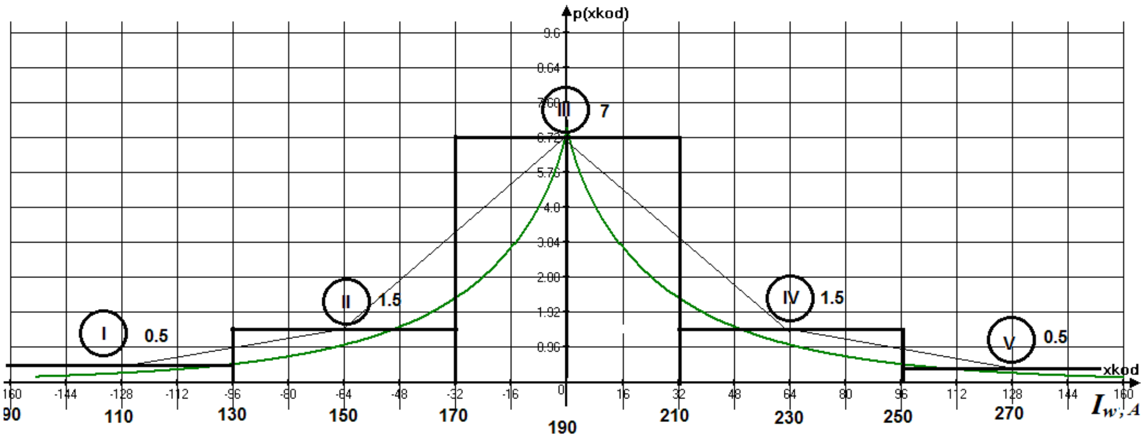


Fig. 5. Histogram, polygon and analytical image of the distribution density of the setting parameter of the welding mode – welding current *Iw*

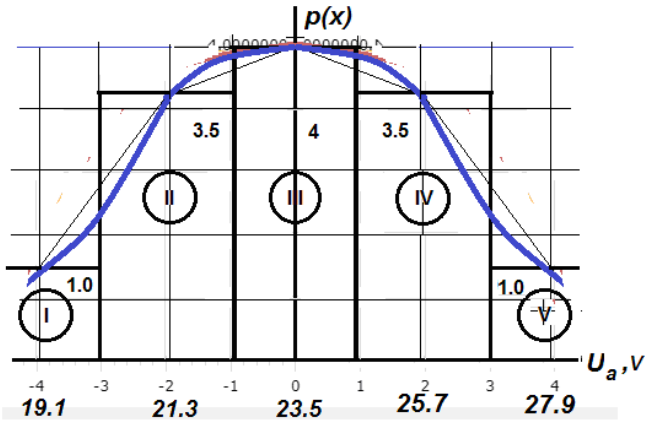


Fig. 6. Histogram, polygon and analytical image of the distribution density of the setting parameter of the welding mode – welding voltage *Ua*

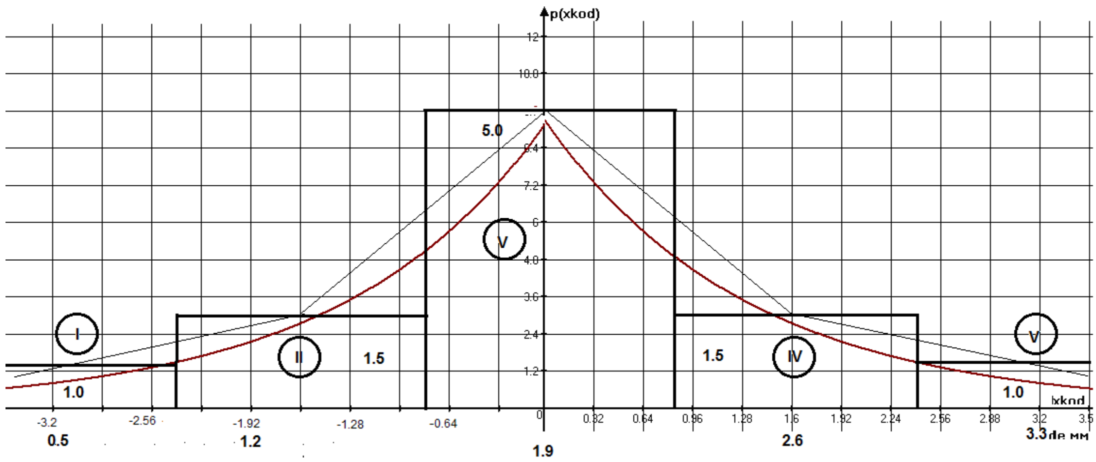


Fig. 7. Histogram, polygon and analytical image of the distribution density of the setting parameter of the welding mode – wire diameter *de*

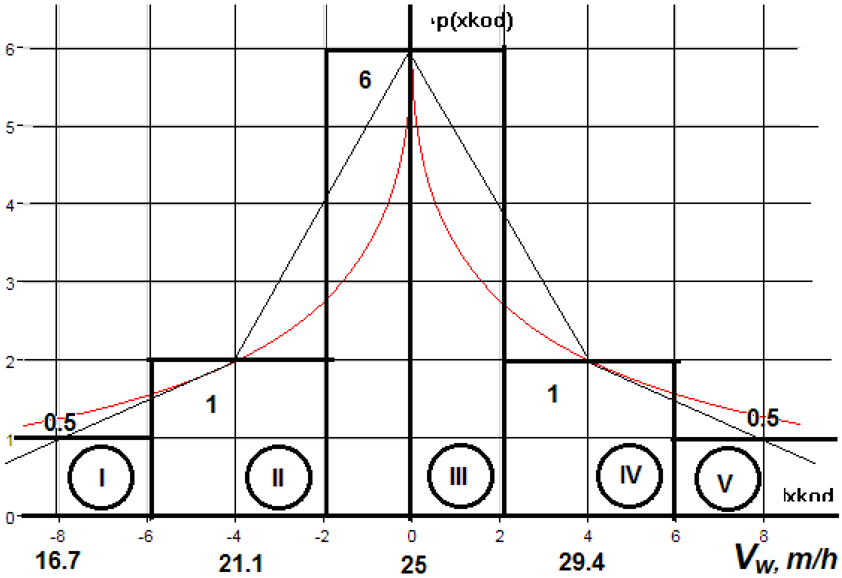


Fig. 8. Histogram, polygon and analytical image of the distribution density of the setting parameter of the welding mode – welding speed *Vw*

The main setting parameter of arc fusion welding processes is the value of the welding current, which, all other things being equal, ensures the specified penetration depth [20]. However, for classic welding sources, this parameter is not set directly, but becomes dependent on the adjustable parameters – wire feed speed and welding voltage. This means that the real value of the current is

$$I_w = -\frac{U_e}{2 \cdot R_B} + \sqrt{\frac{U_e^2}{4R_B^2} + \frac{P_e}{R_B}}, \tag{4}$$

where $U_e = U_{an} + U_B$ is the sum of the voltage drop in the anode part of the arc and the extension of the electrode wire; $P_e = P_B + P_a = I_w(U_a + I_w \cdot R_B)$ – the power is determined by the operation of the current at the outlet of the electrode *le* and the arc.

For a stable quality of seam formation, the above condition must be $P_e = P_B + P_a = const$, which in turn requires a constant wire feed speed $V_{fs} = const$.

Thus, the set of setting parameters is a poorly organized control system, the best technique for its optimization is the planning of the experiment.

A central, composite, symmetrical, 3-level plan is chosen. It belongs to D-optimal plans, which allow the description of a relatively large area of optimization (Table 2).

The variance of the experimental error for the core of the plan* is

$$S_e^2 = \sqrt{\sum_1^n \sum_1^m (\bar{y}_i - \bar{y})^2 \ (m-1) \ / \ n \sum_1^m (m_i - 1)} \ , = 0.595, \tag{5}$$

where *n*= 6 is the number of plan points with duplicated experiments; *m* =2 – the number of takes at the point of the plan.

Homogeneity of variances according to the Cochren criterion

$$G = \frac{S_{i\max}^2}{\sum_1^6 S_i^2} = \frac{1.88}{3.57} = 0.527 \le G_T^{0.05} = 0.602, \tag{6}$$

where S_{imax}^2 $\sum_1^6 S_i^2$ – is, respectively, the largest measurement variance and the sum of measurement variances for the central part of the plan (core).

When processing the results, finding the coefficients of the second-order model of the form b_0, b_i, b_{ij}, b_{2ii} in the form of a polynomial

$$z(\overline{x}) = \overline{F}^T(\overline{x})\overline{b} = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i \le j}^{n} b_{ij} x_i x_j + \sum_{i=1}^{n} b_{ii} x_i^2. \quad (7)$$

The coefficients were calculated according to the form:

$$b_0 = D_1 \sum_1^N \overline{y}_i - D_2 \sum_1^k \sum_1^N \overline{x}_i^2 \overline{y}_i ; b_i = D_3 \sum_1^N \overline{x}_i \overline{y}_i ; b_{ii} = D_4 \sum_1^N \overline{x}_i \overline{y}_i + D_5 \sum_1^k \sum_1^N \overline{x}_i \overline{y}_i - D_2 \sum_1^N \overline{y}_i$$
$$b_{ij} = D_6 \sum_1^N \overline{x}_i \overline{x}_j \overline{y}_n \quad (8)$$

and table coefficients (Table 3)

Table 2

Experiment implementation matrix

№	*x0*	*X1*	*X2*	*X3*	h_d, мм
1	1	20 (-1)	16 (-1)	20(-1)	2.1
2	1	20 (-1)	16 (-1)	30(1)	1.5
3	1	20 (-1)	26(1)	20(-1)	2.3
4	1	20 (-1)	26(1)	30(1)	1.7
5	1	28 (1)	16 (-1)	20(-1)	2.4
6	1	28 (1)	16 (-1)	30(1)	1.1
7	1	28 (1)	16 (-1)	20(-1)	2.3
8	1	28 (1)	26(1)	30(1)	2.6
9	1	24(0)	21(0)	20(-1)	2.4*
10	1	24(0)	21(0)	30(1)	2.3*
11	1	24(0)	16 (-1)	25(0)	2.2*
12	1	24(0)	26(1)	25(0)	2.3*
13	1	20 (-1)	21(0)	25(0)	2.4*
14	1	28 (1)	21(0)	25(0)	2.2*

Table 3

Correction coefficients for calculating model parameters

D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}
0.16634	0.05679	0.07322	0.06247	0.069	0.125	0.40785	0.27059	0.26337	0.35355

The calculated coefficients of the model are shown in Table 4.

Table 4

B_0	B_1	B_2	B_3	B_{12}	B_{13}	B_{23}	B_{11}	B_{22}	B_{33}
5.583	0.0951	-0.3515	-0.0439	-0.0625	0.0125	-0.1125	-1.476	-1.382	-1.4072

The mean square deviation of the coefficients of the model are calculated as (Table 5)

$$S_{b0} = D_7 \cdot \sqrt{S_e^2}; S_{bi} = D_8 \cdot \sqrt{S_e^2}; S_{bi\,j} = D_9 \cdot \sqrt{S_e^2}; S_{bii} = D_{108} \cdot \sqrt{S_e^2} \quad (9)$$

and the confidence intervals of the model coefficients at the statistical confidence level of 95 % (α = 0.05) and the degree of freedom f = 14, respectively, and the tabular value of the Student's criterion $t_{T,\alpha,f}$ =2.131 are calculated as (Table 6)

$$\Delta b_0 = t_{T,f,f} \cdot S_{b0;} \Delta b_i = t_{T,f,f} \cdot S_{bi}; \Delta b_{ij} = t_{T,f,f} \cdot S_{bij}; \Delta b_{ii} = t_{T,f,f} \cdot S_{bii}. \quad (10)$$

Table 5

Mean square deviation of model coefficients

S_{B0}	S_{B1}	S_{B2}	S_{B3}	S_{B12}	S_{B13}	S_{B23}	S_{B11}	S_{B22}	S_{B33}
0.669	0.445	0.445	0.445	0.548	0.548	0.548	0.2726	0.2726	0.2726

Table 6

Confidence intervals of model coefficients

ΔB_0	ΔB_1	ΔB_2	ΔB_3	ΔB_{12}	ΔB_{13}	ΔB_{23}	ΔB_{11}	ΔB_{22}	ΔB_{33}
±1.423	±0.948	±0.948	±0.948	±1.1678	±1.1678	±1.1678	±0.581	±0.581	±0.581

Analysis of the calculated model (11) according to the boundary conditions allows limiting the optimal area of physical existence of the setting parameters of the welding mode (11), namely: source voltage 23.5–24 V, wire feed speed 8.4–52 m/h, welding speed 21.6–23.4 m/h. A graphic representation of the response surfaces of the model and their planar projections are shown in Figs. 9–14.

$$1.476\,x1^2 + 0.0625\,x1\,x2 - 0.0125\,x1\,x3 - 0.095\,x1 + 1.382\,x2^2 + \\ +0.1125\,x2\,x3 + 0.3515\,x2 + 1.4072\,x3^2 + 0.04393\,x3 + z - 5.584 = 0, \\ x1 \approx -1.91493,\quad x2 \approx -0.0830237,\quad x3 \approx -0.0207953, \\ x1 \approx 1.9846,\quad x2 \approx -0.17205,\quad x3 \approx 0.0000828567. \tag{11}$$

The variance of model inadequacy is

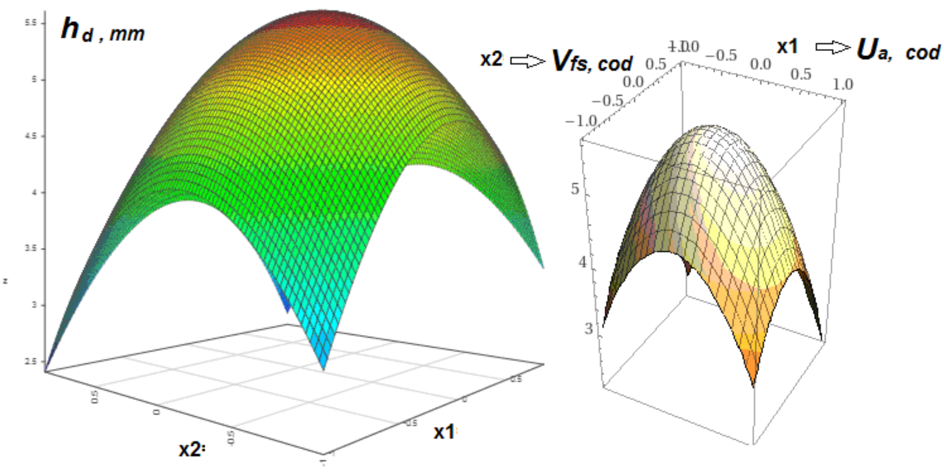
$$S^2{}_{ad} = \frac{\sum_1^{14}(Y_i - Y_i^*)^2}{n-k-1} = \frac{6.32}{10} = 0.632 \tag{12}$$

where Y_i is the value of the penetration height according to the experiment, Y_i* is the same, but predicted by the model; n=14 – the number of experiments according to the plan matrix; k=3 is the number of independent factors of the model.

The goodness-of-fit of the model by Fisher's test is

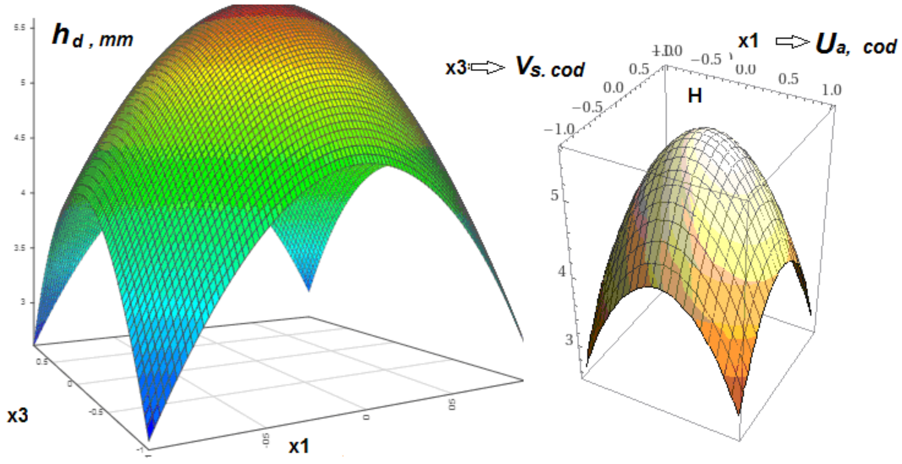
$$F_p \frac{S_{ad}^2}{S_e^2} = \frac{0.632}{0.595} = 1.062 \le F_T = 3.63, \tag{13}$$

where F_T is the tabulated value of the criterion at the accepted confidence probability α=0.05.



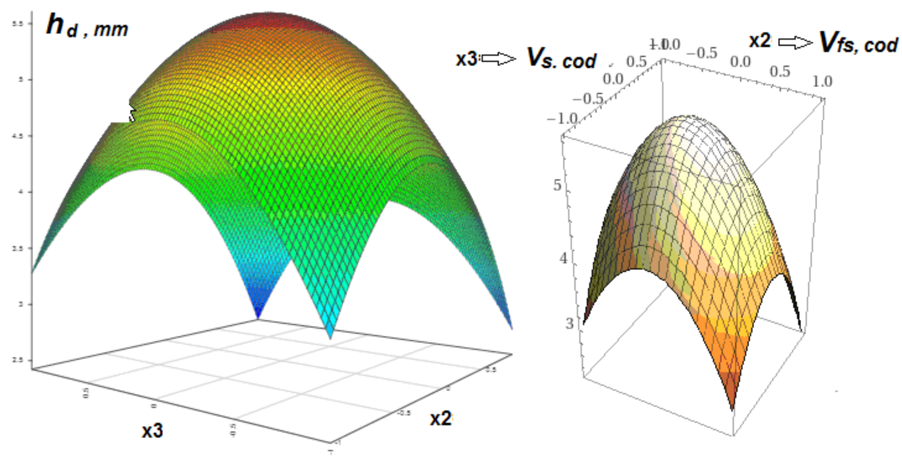
a *b*

Fig. 9. The response surface (depth of penetration) with the interaction of setting parameters (x1 – voltage, x2 – wire feed speed): a – contrast; b – metric



a *b*

Fig. 10. The response surface (depth of penetration) with the interaction of setting parameters (x1 – voltage, x3 – welding speed): a – contrast; b – metric



a *b*

Fig. 11. The response surface (depth of penetration) with the interaction of the setting parameters (x2 – wire feed speed, x3 – welding speed): a – contrast; b – metric

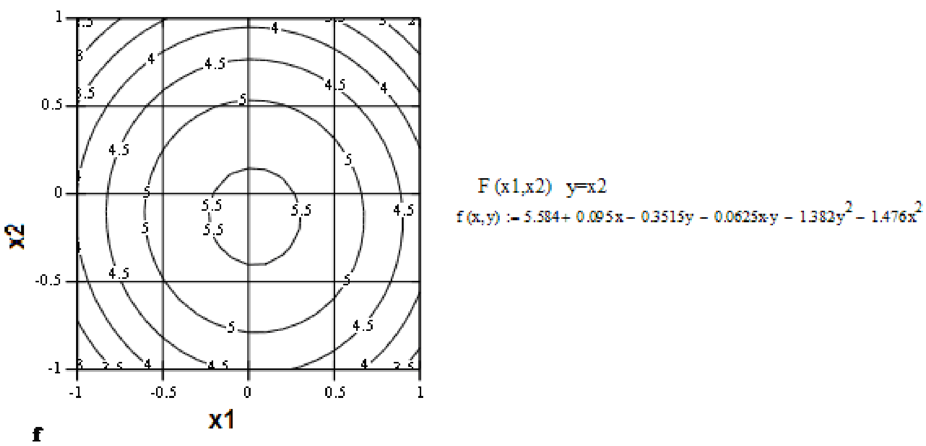


Fig. 12. Sections of the response surface at the interaction of factors x1 and x2(setting parameters of the process – voltage, wire feed speed)

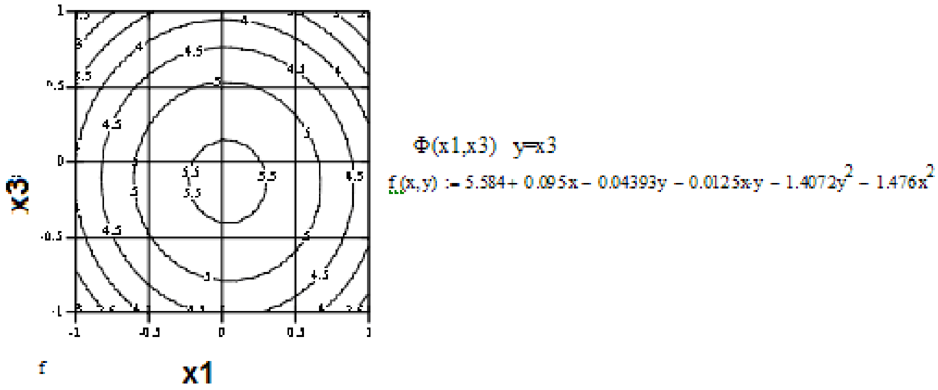


Fig. 13. Sections of the response surface at the interaction of factors x1 and x3 (setting parameters of the process – voltage, welding speed)

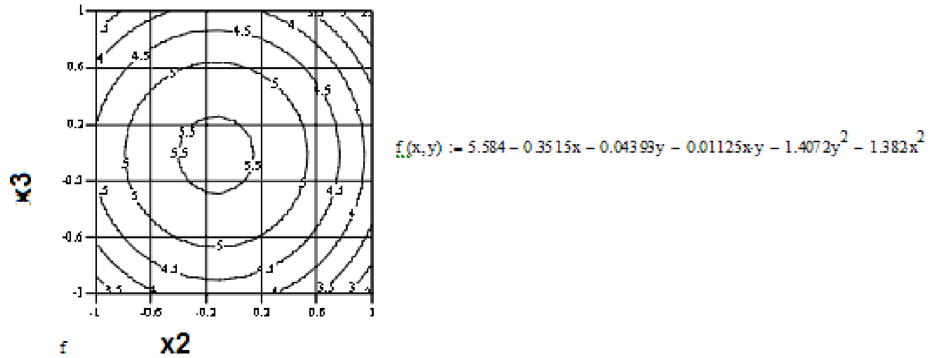


Fig. 14. Sections of the response surface at the interaction of factors x2 and x3 (setting process parameters – wire feed speed, welding speed)

The analysis of the coefficients and signs of the model (19) shows that with a zero coefficient of the model, when the distribution of the data array is accepted as the result of the statistical analysis (the setting parameters of the mode are kept at the average level, the condition of the formation of the weld in one pass is guaranteed to be met. Exceeding the response of the model to the geometry of the seam – the height of the seam 4+1..0.5 mm is explained by the uncertainty interval of the definition of the coefficient itself and by the different assembly and welding conditions from production (Fig. 15).

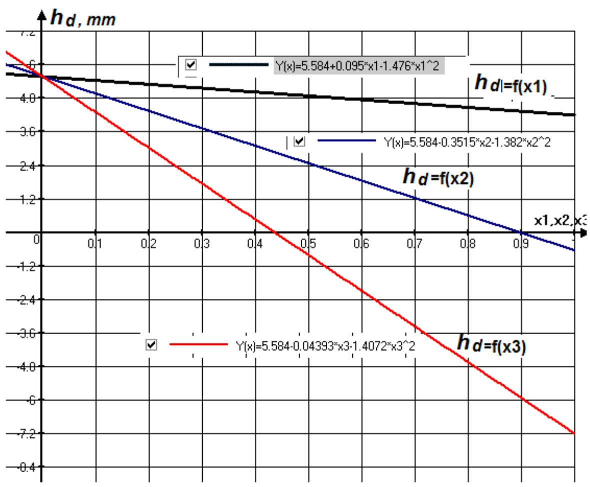


Fig. 15. The effectiveness of adjusting the welding process according to the specified seam height (x1 – voltage, x2 – wire feed speed, x3 – welding speed)

The analysis of the signs of the coefficients of the model clearly indicates the predominant effect of reducing the height of the seam, up to two-pass welding. The positive effect of the welding voltage (X1) and its combined effect with the welding speed (X1X3) are not critical by order of magnitude, in addition, the choice of welding voltage is objectively limited. In fact, this means that the voltage is derived from the list of adjustable parameters, that is, it is set at a given level before welding and is not adjusted during its process. The above is confirmed by the weight factor $k_B = \frac{B_i}{B_{imax}}$=8, where B_i is the value of the coefficient for the linear member of the model relative to the value of the largest coefficient in the linear part of the model. The latter is also confirmed by the weighting factor for interaction effects – in the K_B model for X1X3 it is 9. Its somewhat greater influence is observed in the interaction with the wire feed speed (X1X2) – the weighting factor is 1.8. However, the decision to change the voltage must be strictly coordinated with the change in the wire feed speed – otherwise, the condition of equality of the wire feed speed and its melting speed is violated. The influence of the quadratic components of the model by the weighting factors rather demonstrates not so much their efficiency, but the steepness of the seam height change, that is, it determines a sufficiently narrow range of adjustment by the setting parameters.

As a summary, it can be stated that the necessary and sufficient regulatory parameters are the kinematic indicators of the process – wire feed speed and welding speed at a rigidly specified source voltage. They are significant for all linear, quadratic and interaction coefficients of this model. However, it should be taken into account that the wire feed speed is correlated with the welding current, which, in turn, is determined by the voltage of the welding source. Practically, this means that the quality of welding according to the controllability is determined by the speed of welding, and, accordingly, depends on the qualification of the welder.

In this case, two-pass welding is considered more acceptable when welding “on weight”, which reduces the probability of burning the root of the seam.

Conclusions

1. Based on the processing of the array of recommended data regarding the selection of the value of the setting parameters of the welding process by the procedure of constructing symmetric histograms and the distribution polygon and calculating the analytical model of the description of the distribution density for each setting parameter of the process, their average values are set with a probability of 0.9. The latter are used to calculate the actual values of such parameters for welding a given material thickness.

2. According to the normalized procedure for calculating the value of the setting parameters of the mode, reference indicators are established: the diameter of the electrode wire is 1.6 mm, the welding current is 190 A, the voltage is 25 ± 1 V, the welding speed is 26–42 m/h, the wire feed speed is 21–29 m/h, the output of the electrode wire 16 mm.

3. On the basis of the specified reference base of parameter values, a planned experiment was set up and implemented to find the optimum on a matrix of a composite symmetrical three-level plan, as variable factors are set – process voltage, welding wire feed speed and welding speed; the height of penetration of assembled parts is set by response.

4. Calculation of the coefficients of the model at the level of 0.95, which describes the region of the optimum and the effect of the setting parameters of the mode on it, as well as the analysis of its response surfaces and sections of such surfaces demonstrate that the setting parameter – the source voltage should practically be unchanged at the level of 24V and not has a significant adjustment ability to correct the welding mode. The setting kinematic parameters of the mode are the wire feed speed and the welding speed, respectively 23 and 27 m/h, at the given arc voltage, they provide welding in one pass.

5. In terms of the depth of the ability to adjust the quality of the seam formation, the welding speed prevails, since, all other things being equal, the speed of wire feeding is strictly correlated with the speed of its melting at a given diameter and distance of the electrode. The latter determine the actual value of the current,

the value of which is limited by the source voltage, which is strictly specified and constant for the given process under study.

References

[1] PROCESS – *Surface Tension Transfer* (STT) – Lincoln Electric. https://www.lincolnelectric.com/assets/us/en/literature/nx220.pdf.

[2] Selvi S., Vishvaksenan A., Rajasekar E. "Cold metal transfer (CMT) technology – An overview Defense Technology", *Defense Technology* Vol. 14, Issue 1, February 2018, Pp. 28–44, https://doi.org/10.1016/j.dt.2017.08.002

[3] Holoshubov V. I. *Welding power sources*. K.: Aristei, 2005. 448 p.

[4] *Influence of Metal Transfer Stability and Shielding Gas Composition on CO and CO2 Emissions during Short-circuiting MIG/MAG Welding*// Valter Alves de Meneses , Valdemar Silva Leal , Américo Scotti // Soldagem & Inspeção. 2016;21(3):253–268, https://doi.org/10.1590/0104-9224/SI2103.02

[5] Welding of steels in shielding gases with a melting electrode. *Technics and technology of the future*: monograph / A. G. Potapevskyi, Y. N. Saraev, D. A. Chikhanov; YUTI. Tomsk: TPI, 2012. 208 p.

[6] Belokon V. M. Quality of welding process in protective gases. Bulletin of the Belarusian-Russian University. 2009. No. 3(24). P. 54–61, https://doi.org/10.53078/20778481_2009_3_54

[7] Potapevsky A. H. Welding in shielding gases with a melting electrode. K.: Ekotehnologiya, 2007. 192 p.

[8] Lenivkin V. A., Durgerov N. G., Sagirov H. N. *Technological properties of the welding arc in protective gases.* M.: Mashinostroenie. 1989. 264 p.

[9] Asnys A. E., Gutman A. M., Poklady V. R. *Friction in a mixture of active gases*. K.: Naukova dumka, 1982. 282 p.

[10] Shorshorov M. H., Belov V. V. *Phase transformations and changes in steel properties during welding*. Atlas. M.: Nauka, 1972. 219 p. 251 p.

[11] Brodsky V. Z., Brodsky L. I., Golykova T. I. *Tables of experiment plans for factorial and polynomial models*. M.: Metallurgy. 1982. 752 p.

[12] Parametric Optimization of Gas Metal Arc Welding Processes by Using Factorial Design Approach// Manoj Singla, Dharminder Singh, Dharmpal Deepak // *Journal of Minerals and Materials Characterization and Engineering* > Vol. 9 No. 4, April 2010.

[13] Karadeniz E., Ozsarac, U. and Yildiz, C., "The effect of process parameters on penetration in gas metal arc welding process", *Materials and Design*, 2007, Vol 28, Issue 2, pp. 649–656, https://doi.org/10.1016/j.matdes.2005.07.014

[14] Popkov A. M., Doronyn V. P., Klyashitskaya V. M. Determination of the region of optimal modes of friction in carbon dioxide.- In the book: Questions of friction of the ochno proizvodstvo. *Collection of scientific works of ChP*Y. No. 168. 1975. P. 132–137.

[15] Novitsky P. V., Zograf I. A. *Evaluation of errors in measurement results*. Len-d.: Energoatomizdat. 1985. 248 p.