ALGORITHM OF TECHNOLOGICAL ADAPTATION FOR AUTOMATED MULTIPASS MIG/MAG WELDING OF ITEMS WITH A VARIABLE WIDTH OF EDGE PREPARATION

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Area of research is automation of the processes of multipass MIG/MAG welding of thick-walled items in the downhand position. Objective of research is producing a weld with specified width and reinforcement, not having any lacks-of-penetration or undercuts in the presence of external disturbing influences in the form of a change of geometrical parameters of butt edge preparation (cut-out area). Research task is development of technological adaptation algorithm, which ensures the specified height of welded layer. Research procedure is synthesis of mathematical model based on equations containing both phenomenological descriptions of the processes and regression dependencies. An algorithm is proposed for technological adaptation of butt edge preparation based on machine vision means for multipass MIG/MAG welding. The algorithm ensures calculation of automatic welding mode (voltage, current and speed of welding) in real-time, based on current geometrical parameters of edge preparation. The algorithm uses the developed mathematical of model «power source–arc of steady-state MIG/MAG welding process». In order to verify the algorithm, welding experiments were performed, in which a metal layer of constant thickness of 0.2 cm with varying width of 2.0–3.3 cm was deposited on a steel plate. Range of variation of welding heat input is 4.0–8.5 J/cm with short-circuiting frequency of 5–54 Hz. No arc interruptions were observed, and defects of deposited layer macrostructure were absent. The proposed technological adaptation algorithm can be recommended for application in automatic control systems of multipass welding. 21 Ref., 8 Figures.

Keywords: *multipass MIG/MAG welding, technological adaptation, layer of constant height, mathematical model, welding mode*

Multipass MIG/MAG welding is applied in fabrication and repair of structures of critical items, in order to ensure a high quality of welded joints [1–5]. Application of robotic welding using machine vision means [6] allows ensuring stability and repeatability of the quality of welded joint formation, as it eliminates the subjective factor — welder's qualification. One of the tasks of technological adaptation of multilayer robotic welding is producing a sound weld with the required reinforcement at maximum possible efficiency. The defined task is solved by development of a technological adaptation algorithm, which, proceeding from the current geometrical parameters of the groove, would allow forming the vector of parameters of optimum automatic welding mode: voltage, current and welding speed. Known are the procedures of solving this task based on full-factor active experiments. For instance in [7, 8] the regression models are synthesized, which are used to form optimum control of the welding process.

Development of systems of adaptive control of MIG/MAG welding is now given a lot of attention abroad [9–12]. However, the task of ensuring an optimum mode of multipass welding has not yet been solved completely.

This paper deals with development of technological adaptation algorithm for robotic multipass MIG/MAG welding of massive items in the downhand position.

Let us consider multipass arc welding, in which V-shaped groove (Figure 1, *a*) or cut-out area in the item (Figure 1, *b*) is filled with layers of the same height.

The first step of technological adaptation is scanning of the groove by a laser triangular sensor (LTS). Scanning results are used to draw a conclusion as to whether the geometrical parameters of the groove remain constant or change over its entire length.

In the first case, at constant geometry of the groove (cut-out area) technological adaptation for multipass MIG/MAG welding is associated with bead deposition in different n-th layers (see Figure 1, *a*) and consists in calculation of deposition mode for each k-th bead. Deposition mode

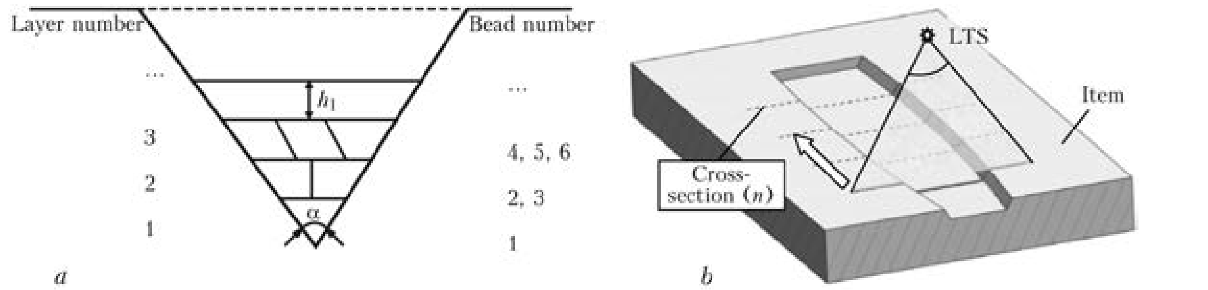

Figure 1. Schematics of multipass welding: *a* — filling of V-shaped groove of constant height layer (α — groove angle; h_l — layer height, cm); *b* — filling the cut-out area in the item (longitudinal welds)

parameters remain constant along the entire length of the deposited bead.

In the second case at variable groove geometry technological adaptation can be associated, for instance, with variation of groove angle along the butt line (see Figure 1, *a*) or with varying shape of cut-out area (see Figure 1, *b*). To compensate for the above-mentioned disturbances, it is necessary to control the welding mode during deposition of each *k*-th bead. Thus, at deposition of a layer of a constant height into a groove of varying width it is necessary to constantly control the cross-section of each bead in the layer in real time.

Formulation of technological adaptation concept for multilayer multipass welding. Let us consider *n*-th cross-section of the deposited layer (Figure 1, *b*), which has the shape of a trapezoid (in the general case, the trapezoid is not isosceles) of area $S_d[n]$ (Figure 2).

We will calculate cross-sectional area $S_d[n]$ by the following formula:

$$S_d[n] = l_{low}[n]h_l + \frac{h_l^2}{2}(\mathrm{tg}\ \theta_{left}[n] + \mathrm{tg}\ \theta_{right}[n]), \quad (1)$$

where $l_{low}[n]$ is the width of layer lower surface, cm; $\theta_{left}[n]$, $\theta_{right}[n]$ is the angle of inclination of the surface of the left and right edge, deg.

Deposited layer consists of a whole number of beads *N*, cross-sectional areas of which $F_d[k]$ for each $S_d[n]$ have the same values:

$$F_d[k] = \frac{S_d[n]}{N}, \quad (2)$$

where *k* is the bead number.

We will calculate bead width $E[k]$ by the following formula:

$$E[k] = \frac{l_{low}[k]}{(N - 2K_{s.ed} - (N - 1)K_{adj.b})}, \quad (3)$$

where $K_{s.ed}$ is the coefficient determining the value of overlapping of extreme beads in each layer with side edges of the item; $K_{adj.b}$ is the coefficient determining the value of overlapping between the adjacent beads in the layer. Here $K_{s.ed} = 0.135$ and $K_{adj.b} = 0.27$.

The objective of this research is development of such an algorithm of adaptive control of welding, which for each $E[k]$ and $F_d[k]$ allows calculation of the following parameters of MIG/MAG welding mode: voltage *U*, current *I* and welding speed v_w.

In the first part of technological adaptation algorithm, required heat input values are determined for calculated values of bead width $E[k]$. Let us consider the case of bead deposition on the surface, of a massive body. Width of the zone on item surface limited by isotherms of melting temperature T_m, can be found from the following equation [13]:

$$E[k] = \sqrt{\frac{8q_h[k]}{\pi e c\gamma\Delta T}}, \quad (4)$$

where $q_h[k]$ is the welding heat input, J/cm; $c\gamma$ is the volumetric heat capacity, J/(cm^3·°C); $\Delta T = (T_m - T_0)$ is the steel melting temperature, °C; T_0 is the initial item temperature, °C; π = = 3.14159265, ε = 2.71828183 are the constants.

Calculations by formula (4) yield heat input values with more than 8 % error [14] that is unacceptable for the defined problem. With the known approach, the calculation accuracy can be increased by introducing an additional coefficient [15]. Correction factor K_q, which reduces the calculation error to 5 %, was determined experimentally for the range of heat input variation from 4200 up to 8400 J/cm. Then, equation (4) is written as follows:

$$q_h[k] = K_q \frac{\pi e}{8} E[k]^2 c\gamma\Delta T, \quad (5)$$

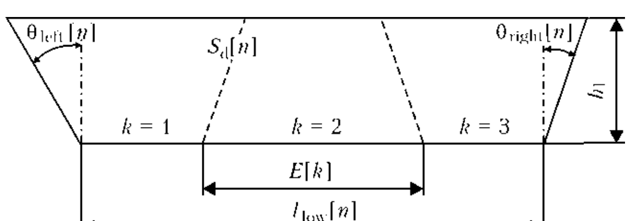

Figure 2. Schematic of *n*-th cross-section of the deposited layer

where $q_h[k]$ are the experimental data of welding heat input, J/cm; $K_q = (1.05–0.6.10^{-4})q_h$. After their substitution equation (5) becomes

$$q_h[k] \cong \frac{1.121\,E[k]^2 c\gamma\Delta T}{1 + 6.405\cdot 10^{-5} E[k]^2 c\gamma\Delta T}. \quad (6)$$

Second part of technological adaptation algorithm is solution of a system of phenomenological and regression equations, describing MIG/MAG welding in the steady state. Input data are bead width $E[k]$, cross-sectional area of deposited bead $F_d[k]$ and welding heat input $q_h[k]$:

$$q_h[k] = \frac{I[k]U[k]\eta_{eff}}{v_w[k]}, \quad (7)$$

$$I[k] = (86.58 + 18.94 v_{w.f}[k] - 4.2U[k] + 0.17 U v_{w.f}[k] - 0.46 v_{w.f}[k]^2 + 0.09 U[k]^2), \quad (8)$$

$$F_d[k] = \frac{\pi d_{el}^2 v_m[k](1 - \psi)}{4 v_w[k]}, \quad (9)$$

$$v_m[k] = \frac{K[k]U[k]j_{el}[k] + 10^4 \rho_{el} j_{el}[k]^2 L_{el}[k]}{M}, \quad (10)$$

$$K[k] = (0.285 - 0.0052\,U[k]), \quad (11)$$

$$j_{el}[k] = \frac{4I[k]}{\pi d_{el}^2}, \quad (12)$$

$$v_m[k] = v_{w.f}[k], \quad (13)$$

where L_{el} is the length of electrode extension, cm; $v_{w.f}$ is the wire feed rate, cm/s; v_m is the average integral value of electrode wire melting rate, cm/s; K is the coefficient, determining the heat consumption for wire heating and melting, 1/cm^2; M is the thermophysical constant of electrode wire, J/cm^3; d_{el} = 0.12 cm is the electrode diameter; j_{el} is the electrode wire current density, A/cm^2; ρ_{el} is the average value of specific electrical resistance of electrode metal, Ohm/cm; η_{eff} is the effective efficiency of the process of item heating by the arc; ψ is the coefficient allowing for filler metal losses for spattering and evaporation.

Value $q_h[k]$ is found from formula (7) [16]. Equation (8) is a regression equation and allows calculation of electrode wire feed rate. It is synthesized by the authors for MIG/MAG welding mode with the following values: arc power source Fronius TransPuls Synergic-5000 at reverse polarity in shielding gas atmosphere of Ar + + 18 % CO_2, electrode diameter of 0.12 cm, welding current range of 200–300 A and welding voltage of 22–30 V. Value of cross-sectional area of the deposited bead is calculated from equation (7) [1]. Wire melting rate is calculated from equations (10), (11) for the steady-state mode of MIG/MAG welding at variation of welding voltage in the range of 15–35 V [17]. Current density in a round conductor is calculated from equation (12). Equation (13) describes the stability of the process of drop transfer in power source–arc system in MIG/MAG welding.

Solution of a system of equations (7)–(13) yields the required values of wire feed rate $v_{w.f}[k]$, welding voltage $U[k]$ and welding speed $v_w[k]$ for k-th section of the current bead of a multipass weld.

Investigation of the system of equations (6)–(13) shows that in many cases a unique solution cannot be obtained. Therefore, it is rational to apply a method of searching for a numerical solution by the criterion of minimum mean-root-square error. With this purpose additional conditions were defined, which, first of all, ensure a steady-state mode of MIG/MAG welding [18]; secondly minimize the mean-root-square error of the solution; and thirdly provide maximum efficiency of the welding process. As a result, the following system of inequalities was derived, which specifies the constraints for an algorithm of searching for a solution of the system of equations (6)–(13):

$$I_{min} < I[k] < I_{max}, \quad (14)$$

$$A_3 I[k] < U[k] < A_4 I[k], \quad (15)$$

$$\delta_{F_d[k]} = \sqrt{\left(\frac{\left(\dfrac{F_d[k] - \pi(d_{el})^2 v_m[k](1 - \psi)}{4 v_w[k]}\right)}{F_d[k]}\right)^2} < \delta_{F_{d\,max}}, \quad (16)$$

$$\delta_{v_{w.f}[k]} = \sqrt{\left(\frac{v_{w.f}[k] - v_m[k]}{v_{w.f}[k]}\right)^2} < \delta_{v_{w.f\,max}}, \quad (17)$$

$$v_w[k] > v_{w\,min}, \quad (18)$$

where I_{min}, I_{max} are the values of the upper and lower limit for welding current; A_3, A_4 are the coefficients assigning the constraints for welding voltage, which ensure a steady-state mode of MIG/MAG welding in the selected range of welding currents [18, 19]; δ_{F_d}, $\delta_{v_{w.f}}$ are the relative actual and maximum admissible error between the calculated and specified value of deposit cross-section; $\delta_{v_{w.f}}$, $\delta_{v_{w.f\,max}}$ are the relative actual and maximum admissible deviation of the calculated value of wire feed rate relative to its melting rate; $v_{w\ min}$ is the minimum value of welding speed, at which the required level of cost-effectiveness at application of automatic multipass welding is achieved.

A simultaneous solution of a system of equations (6)–(13) and constraints (14)–(18) was derived using non-linear hill climbing techniques such as Levenberg–Marquardt algorithm, conjugate gradient or quasi-Newton methods [20]. Mathematical model and its solution algorithms were constructed in Mathcad mathematical package using «Minerr» operator [21] that allows assigning one of the three solution methods: Levenberg–Marquardt, Conjugate Gradient or Quasi-Newton, respectively.

As an example, the problem of deposition of a layer of 0.2 cm height with varying width from 2.0 up to 3.3 cm on a carbon steel plate of 1.2 cm thickness was solved. Electrode wire material is Sv-08G2S-0. Geometrical parameters $S_d[n]$ are calculated with 3 cm step by formula (1), based on geometrical characteristics of the projections of laser plane on the groove of the item being welded, obtained using LTS. As a result, the geometrical model of variation of the layer cross-section is a curve consisting of line segments, connecting the adjacent points of calculated values of $S_d[n]$, where n = 1–8, depending on longitudinal coordinate x (Figure 3).

Note that two points with numbers 2 and 7 were added on purpose in order to ensure correct performance of technological operations of «arc ignition» and «crater welding up».

Proceeding from the general geometrical model of a multipass weld, trajectories of torch displacement for welding three filling beads and two auxiliary (extreme) beads, which simulate the edges of cut-out area (Figure 4), were formed. Consideration of the problem of calculation of torch trajectories for automatic multipass welding is beyond the scope of this paper.

Proceeding from the results of analysis of the minimum and maximum values of layer cross-sections (see Figure 3) and allowing for the range of heat input values of 4200–8400 J/cm admissible for the developed mathematical model, we will calculate the required number of beads in the layer as 3. We assume that the cross-sectional areas of all the filling beads $F_d[k]$ are the same in the same layer section. Therefore, the file of initial values of bead cross-sections is as follows:

$$F_d[k] = (0.128;\ 0.136;\ 0.168;\ 0.194;\ 0.205;\ 0.201;\ 0.185;\ 0.181),\ \text{cm}^2. \quad (19)$$

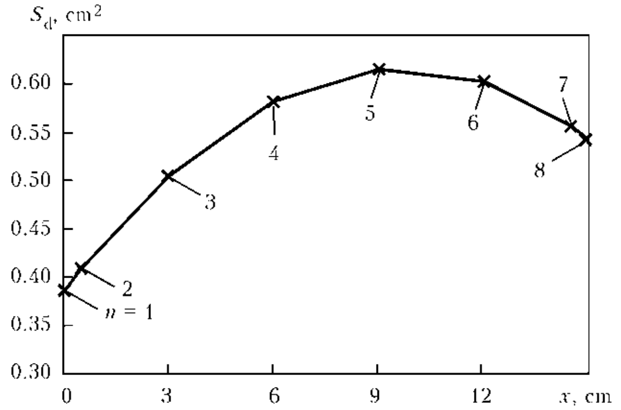

Figure 3. Curve of variation of deposited layer cross-section (linear interpolation between the calculated points was used)

We find the file of bead width values from formula (3) as follows:

$$E[k] = (0.83;\ 0.88;\ 1.10;\ 1.27;\ 1.35;\ 1.32;\ 1.22;\ 1.18),\ \text{cm}. \quad (20)$$

We obtain the data file for welding heat input by formula (6):

$$q_h[k] = (4244,\ 4651,\ 6344,\ 7592,\ 8091,\ 7902,\ 7177,\ 6964),\ \text{J/cm}. \quad (21)$$

Calculation of welding modes is performed at the following values of thermophysical and technological constants: $\eta_{eff} = 0.8$; $c\gamma = 4.9$ J/(cm^3·°C); ψ = 0.1; ρ_{el} = 0.777·10^{-6} Ohm/cm; M = 9.75·10^3 J/cm^3; T_m = 1520 °C; T_0 = 200 °C; I_{min} = 195 A; I_{max} = 300 A; A_3 = 0.1; A_4 = 0.116; $v_{w\ min}$ = 0.75 cm/s; $\delta_{F_{d\ max}}$ = 0.05; $\delta_{v_{w.f\ max}}$ = 0.1.

Mathcad package was used to search for a solution. Application of Levenberg–Marquardt technique to system of equations (7)–(13) with constrains (14)–(18) allowed deriving the following values of parameters of multipass welding mode:

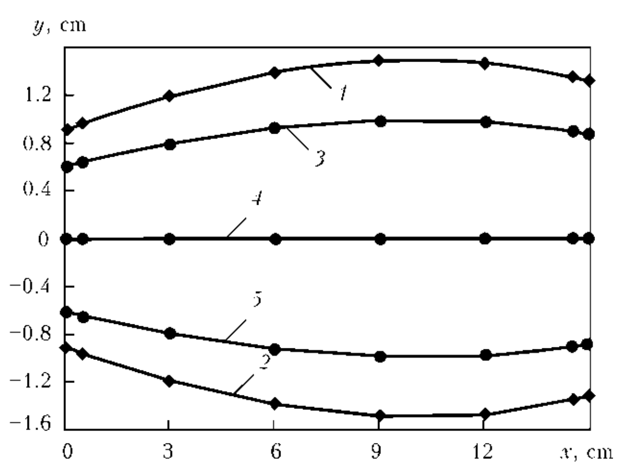

Figure 4. Trajectories of torch displacement at layer deposition: x, y — coordinates of longitudinal and transverse displacement of the torch; *1*, *2* — auxiliary extreme beads; *3*–*5* — main filling beads

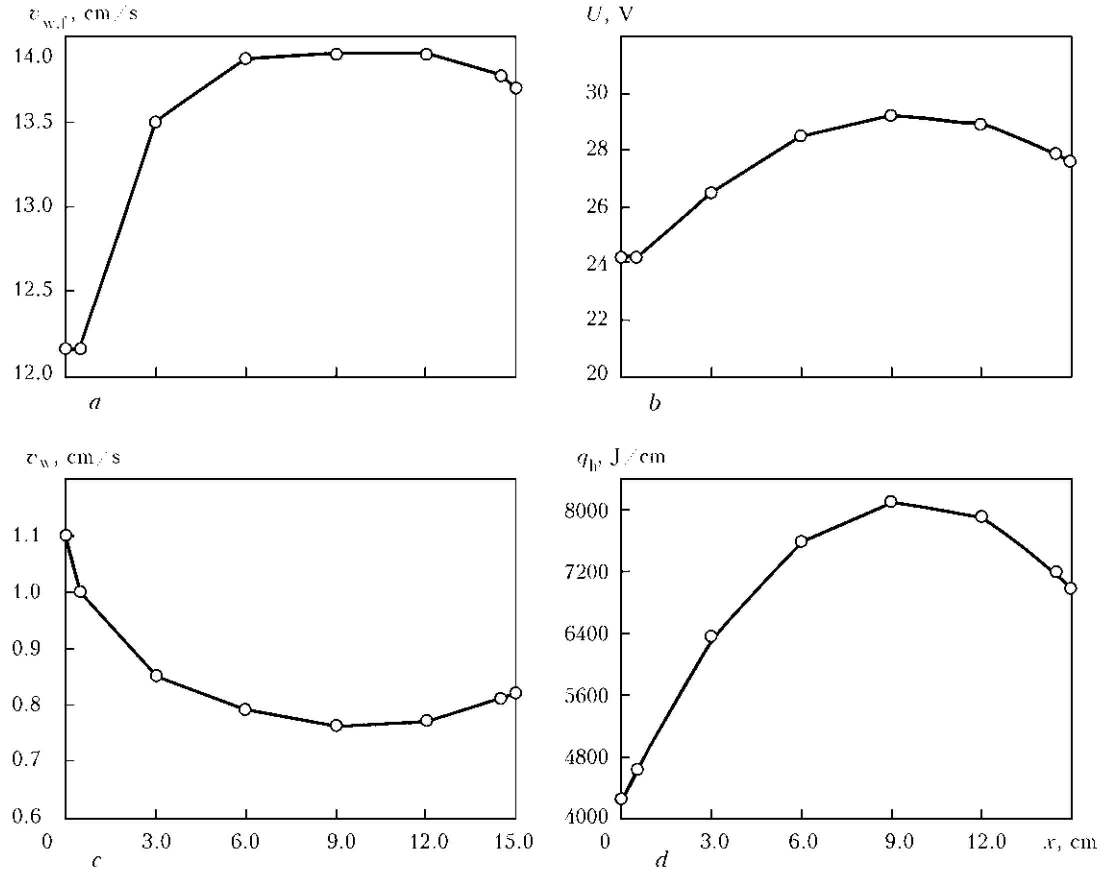

Figure 5. Curves of variation of mode parameters of bead welding at deposition of multipass layer of varying width

$$v_{w.f}[k] = (12.16;\ 12.16;\ 13.50;\ 13.87;\ 13.90;\ 13.90;\ 13.77;\ 13.70),\ cm/s, \quad (22)$$

$$U[k] = (24.2;\ 24.2;\ 26.5;\ 28.5;\ 29.2;\ 28.9;\ 27.9;\ 27.6),\ V, \quad (23)$$

$$v_w[k] = (1.1;\ 1.0;\ 0.85;\ 0.79;\ 0.76;\ 0.77;\ 0.81;\ 0.82),\ cm/s, \quad (24)$$

$$\delta_{F_d[k]}\cdot 100 = (4.6;\ 3.4;\ -1.1;\ 2.1;\ 3.3;\ 2.8;\ 1.1;\ 0.6),\ \%, \quad (25)$$

$$\delta_{v_{w.f}[k]}\cdot 100 = (8.0;\ 8.0;\ 11.5;\ 16.1;\ 17.5;\ 17.0;\ 14.8;\ 14.1),\ \%. \quad (26)$$

When assigning the current welding mode, intermediate values for mode parameters were calculated by the method of linear interpolation. Graphs of the resulting functions are shown in Figure 5 (graph of q_h variation is given to verify the calculations).

Note that calculation of welding modes using Mathcad «Minerr» operator in PC with Intel Core(TM)2 Quad CPU 2.50GHz processor and RAM volume of 2 GB takes less than 1 s. Therefore, such an approach can be used in adaptive control system in real time.

Analysis of derived solutions for multipass welding modes shows that anticipated errors of bead formation by such parameters as deposit section and bead width do not exceed 5 % that guarantees uniform deposition of the layer. Mismatch of melting rates and electrode wire feed rates does not exceed 20 %. Calculated modes of multipass MIG/MAG welding provide a high efficiency of technological operation of deposition of 0.2 cm layer: welding speed varies from 0.76 up to 1.1 cm/s, and welding current — from 241 up to 262 A.

Experimental verification of technological adaptation algorithm. To verify the calculated modes of multipass welding, experiments were conducted on deposition of 0.2 cm thick layer on a low-carbon steel plate. Deposited layer consisted of five beads: two auxiliary, which simulate the cut-out area edges, and three filling beads. Welding was performed in a mixture of gases of Ar + 18 % CO_2 (25 l/min), d_{el} = 0.12 cm, L_{el} = = 1.4 cm. Item temperature was measured by chromel-alumel thermocouples that allowed controlling preheating temperature T_0, using technological pauses between bead deposition. As is seen from the deposited layer appearance (Figure 6), values of overlapping between the beads correspond to specified values, while losses for evaporation and spatter are satisfactory.

Analysis of welding process stability was performed on the basis of recorded and averaged values (trends) of U, I, $v_{w.f}$ and frequency of

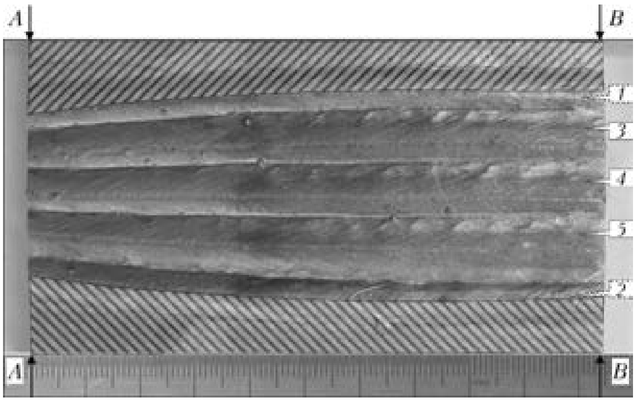

Figure 6. Macrosection of deposited layer (hatched regions simulate sectional view of the cut-out area): *1*, *2* — auxiliary extreme beads; *3*–*5* — main filling beads

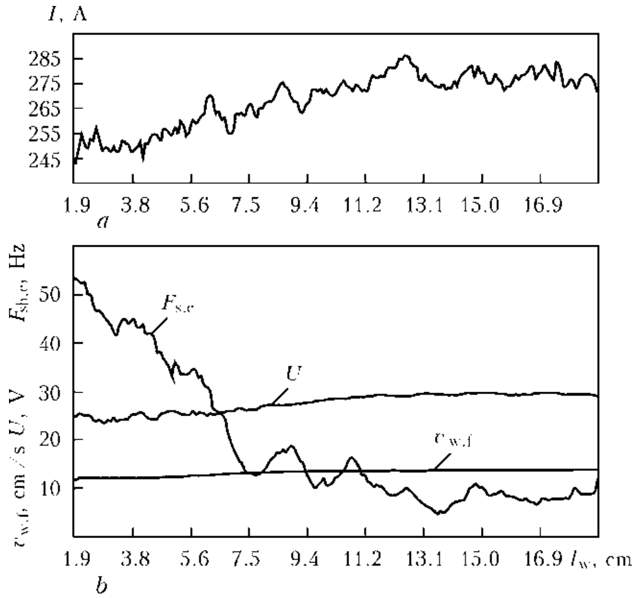

Figure 7. Trends of variation of MIG/MAG welding parameters at realization of technological adaptation algorithm (bead 3): *a* — welding current; *b* — frequency of arc gap short-circuiting, welding voltage and wire feed rate

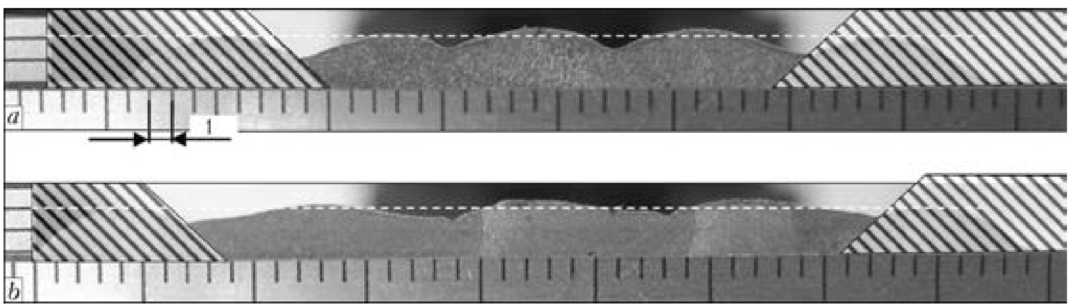

Figure 8. Macrosections of deposited layer using multipass MIG/MAG welding (hatched regions simulate section view of cut-out area): *a* — layer initial section (*A*–*A* section in Figure 6); *b* — layer end section (*B*–*B* section in Figure 6)

arc gap short-circuiting $F_{sh.c}$. Figure 7 shows the trends of technological parameters of welding bead 3 along the entire weld length l_w (except for «arc ignition» and «crater welding-up» intervals). Analysis of derived trends shows that the actual changes of welding mode parameters corresponded to calculated curves of setting variations (see Figure 5). Process of MIG/MAG welding was of a steady nature. Parameter $F_{sh.c}$ varied in the range from 54 to 5 Hz that corresponds to admissible in MIG/MAG welding variation of drop transfer mode from fine- to coarse-drop transfer. No arc interruptions were observed.

Analysis of deposited layer macrosection was performed (Figure 8), which demonstrated the good quality of the deposited layer, in which slag inclusions or pores were absent. Errors by width and height of the deposited layer do not exceed 5 %. Layer height (hatched line in Figure 8) remains constant along its entire length.

Results of experimental verification of the developed algorithm of technological adaptation show that the proposed algorithm of welding mode control by I, U and v_w allows producing a layer of specified width and height without defects. High speed of welding mode calculation allows application of the developed algorithm in systems of technological adaptation for robotic multipass MIG/MAG welding of thick items with variable width of edge preparation.

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NEWS

High-Speed Electroslag Welding of Thick-Plate Metal without Normalization of Welded Joints

When the traditional ESW is used, the separate regions with a reduced resistance to brittle fracture as compared to that of parent metal are observed in the welded joint. As a rule, the heterogeneity of structure and mechanical properties in these regions is eliminated by the application of postweld high-temperature treatment, for example, normalization. However, it leads to an abrupt increase in cost of the product manufacture.

The new method of a high-speed ESW with an automatic commutation of current connectors to a group of electrodes and edges of welded joints and equipment for its realization have been developed, allowing producing quality welded joints without postweld high-temperature treatment.

To realize the new technological process of ESW, the automatic two- and three-channel commutators of alternating (combined) current (current of up to 6 kA, 1–17 Hz frequency, 2–6 on–off time ratio) and two-channel direct current (1.5 kA current, 10 Hz frequency, 2–6 on–off time ratio) have been designed, which are compatible with existing serial power sources. Controllers and sensors of metal pool molten metal level, voltage stabilizers at the slag pool, digital meters of electrode wire feed speed, have been designed, having no analogues in the national and foreign engineering.

The new technological process makes it possible to weld steels of 40–150 mm thickness at high efficiency (3–6 m/h welding speed) and lower specific energy input (4–6 times reduced as compared with that of conventional conditions) at 3–4 times decrease of power consumption as compared with conventional ESW for the above-mentioned thicknesses.

Completion of repair of blast furnace (inside view) at «Krivorozhstal» Works. As-welded part of wall is shown

Field of application. Welding of thick-plate steels in shipbuilding, reactor construction, boiler and converter production, hydro-engineering works, cryogenic engineering, cement machine building (steels of 25KhN3MFA, 16GNMA, 20K, 22K, 16GS, 09G2S, 03Kh20N16AG6, 10KhSND, 25L, 25GSL, 35L and other types), as well as control of structure of welds in ESW of copper, titanium alloys.

Pollutions of toxic elements are 3–4 times reduced as compared with conventional ESW.

Equipment has been implemented at the number of metallurgical and machine-building plants of CIS, including «Ukrtsemremont» (Zdolbunov city) for welding of kiln furnace bands, «Sibenergomash» (Barnaul city) for welding of boiler fragments of 90, 110 and 150 mm thickness, made of steels 16GS, 22K and 16GNMA, as well as in repair of body of blast furnace DP-9 and assembly of converter body at «Krivorozhstal» Metallurgical Works (Krivoj Rog city).