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INTENSIFICATION OF ARC AND ELECTROSLAG PROCESSES OF WELDING BY MEANS OF EXOTHERMAL MIXTURE INTRODUCTION

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It is proved that introduction of up to 53.4 % of exothermal mixture in electrode coating results in increase of the following coefficients, i.e. core melting, deposition, rate of electrode melting and melting of electrode coating. Increase of thickness of electrode coating, containing 44.4 % of exothermal mixture, from 0.5 to 2.6 mm results in rise of amount of exothermal mixture and deposition coefficient, decrease of value of core melting coefficient, increase of mass rate of coating melting. It is proved that an efficient method for increase of electroslag processes efficiency is application of exothermal flux, namely scale, ferroalloys, aluminum powder and standard flux (ANF-6 etc.) in the amounts sufficient for exothermal reaction passing. This provides for emission of additional heat in a start period of exothermal processes and promotes for accelerated formation of slag pool of necessary volume on «solid» start on monofilar as well as bifilar schemes of process instead of «liquid» start. The electroslag processes using exothermal alloyed flux on «solid» start allow (in comparison with existing methods of slag pool formation) rising metal yield by 2–10 %; 1.2–1.4 kW·h economy of melting of 1 kg of standard flux; 25 % reduction of time of ESR process start period. It is determined that introduction of aluminum as a deoxidizing agent in the exothermal fluxes rises content of aluminum oxide (Al_2O_3) in a weld pool, its resistance, and increases efficiency of electroslag process. 21 Ref., 5 Figures.

Keywords: *electrode, exothermal mixture, exothermal flux, slag pool, process efficiency*

Currently coated electrode manual arc welding is still one of the widely applied technological processes. Volume of works performed using manual arc welding in industrially-developed countries makes 20–25 % from total volume and in post-soviet countries it reaches 60–70 % [1–4]. Particularly high index is observed in building industry. It can exceed 80–85 % [2, 3]. This requires paying serious attention to improvement of manual arc welding. First of all, it concerns development of high-efficiency welding electrodes, one of the main factors determining process efficiency of welding [5–8].

One of the important problems of welding consumable developers is searching the new types of raw materials for their manufacture and determination of the ways for intensification of welding and metallurgical processes. One of the directions for solving this problem is application of effect of exothermal reactions through introduction of the exothermal metal-flux mixtures in welding consumable composition. They pass electric current in solid state and represent themselves mechanical mixture of scale, aluminum powder, alloying elements (in form of ferroalloys or powders) and working flux (for example, ANF-6 or other).

This problem can be solved using the effect of exothermal reactions in the electrode coating before its core melting by means of introduction in the coating composition the materials used in form of oxidizers (scale, hematite, manganese ore etc.) and deoxidizers (ferrotitanium, ferrosilicium, aluminum powder etc.). It should be noted that data on influence of heat effect of the exothermal reactions on welding-technological properties of the electrodes are limited in the special literature [9–11].

Iron oxides introduced in the electrode coating in form of scale allow using an effect of increase of bulk weight of iron powder and its positive effect on workability of electrode production. Besides, melting of the electrode coating with exothermal mixture provokes exothermal reaction and formation of reduced iron coming into weld. This rises efficiency of welding process and due to emitted heat promotes acceleration of coating melting and electrode in whole.

It is known fact [12–14] that the exothermal reaction results in emission of additional heat power. It is determined [13] that amount of heat consumed by exothermal reaction for heating and melting of the electrode core reaches 10 kJ/s value. This is enough for uniform melting of core and shell. Melting efficiency of flux-cored strips rises by 40–60 % and that of deposition by 30 %. Besides, power saving is obtained (1500 kW·h per 1 t of the deposited metal).

The aim of this paper is intensification of manual arc welding and electroslag processes by means of development of welding consumables using exothermal mixtures in their production.

Electrodes currently applied in industry for welding and surfacing are characterized by low efficiency (deposition coefficient does not exceed 8.5–9.5 g/A·h), therefore increase of efficiency of manual arc welding (surfacing) and searching the new types of raw materials for their manufacture is one of the main problems for surfacing consumable developers.

Introduction of iron powder in composition of the electrode coating is one of the main ways increasing efficiency of manual arc welding (surfacing). Content of iron powder in the electrodes in 15–25 % range improves their welding-technological properties without significant change of the deposition coefficient. The largest efficiency is reached at content of iron powder in the electrode coating in the amount of 60–70 % at coating mass coefficient in 100–200 % range (such electrodes are called «high-efficient»). However, specific weight of the «high-efficient» electrodes used in our country (due to necessity of application in this case of power sources with increased open — circuit voltage, scarcity of iron powder, complexity in providing their quality production in continuous production lines «electrode press–conveyor calcining furnace») is very low. Further growth of efficiency of electrode advanced grades is also limited by scarcity (on the world market as well as in our country) of series of raw materials such as iron powder, rutile concentrate etc.

The aim stated in present work was solved applying exothermal metal-flux mixtures, representing themselves mechanical mixture of scale, aluminum powder, alloying elements in form of ferroalloys (ferromanganese, ferrotitanium, ferrosilicium) in manual arc welding and exothermal fluxes (exothermal mixture + standard flux) in electroslag processes.

Welding processes can be intensified by introduction of exothermal mixtures in the welding consumable composition. Carried investigations [15] determined that variation of a content of exothermal mixture in the electrode coating from 35 to 64 % provides for 1280 °C growth of temperature, which is sufficient for complete melting of ferroalloy.

Rate and efficiency of electrode melting, evaluated mainly by change of length or mass of the molten electrode core per unit of time, is an important characteristic of welding process and depends on number of factors, main of which are welding current, coating composition, current type and polarity.

Introduction in the electrode core of exothermal mixture provokes emission of additional amount of heat due to chemical reaction taking place between iron oxides and elementsal-deoxidizers. The largest amount of heat is emitted at interaction of aluminum with ferrous oxide, and the lowest at manganese with ferrous oxide interaction (q^{Al} = 3268, q^{Ti} = 2171.1, q^{Si} = 2224.7, q^{Mn} = 950.8 J/g).

Electrodes containing in the coating marble, fluorspar, rutile concentrate, ferromanganese, ferrotitanium, iron scale and aluminum powder and having 5.0 mm core diameter and different content of exothermal mixture at constant value of coefficient of coating mass (K_c = 0.6) were manufactured for determination of effect of amount of exothermal mixture on indices of electrode melting. Melting of the electrodes was carried out at similar values of welding current (290 A) and its density (24.8 A/mm^2) at 60 V open-circuit voltage of power source. The electrodes of 5.0 mm core diameter and coating thickness of 0.5–2.6 mm that corresponded to variation of coefficient of coating mass from 0.17 to 1.14 were manufactured for determination of effect of thickness of the electrode coating with exothermal mixture on process characteristics of their melting. Amount of exothermal mixture in the studied electrodes made 44.4 % of coating mass.

Values of experimental data are given in Figure 1. It is proved that introduction of exothermal mixture in the electrode coatings (Figure 1, *a*) results in increase of the following coefficients, namely melting of core ($\alpha_{m.cr}$ = 8.7–11.4 g/A·h), deposition (8.0–12.5 g/A·h), electrode melting (9–19 g/A·h), and electrode melting rate (17–23 m/h) [16, 17].

Experiments showed that increase of electrode coating thickness (Figure 1, *b*) results in rise of amount of exothermal mixture, reduced iron and deposition coefficient (α_d = 10.4–13.4 g/A·h), decrease of coefficient of melted core ($\alpha_{m.cr}$ = 12.8–10.5 g/A·h) and rate of electrode melting (21.5–18.3 m/h). Reduction of $\alpha_{m.cr.}$ with rise of the coating thickness indicates that heat being formed during exothermal reaction is mainly spent for coating melting, increasing its mass rate of melting (0.18–1.03 g/s).

Determination of effect of amount of exothermal mixture and electrode coating thickness with exothermal mixture on heating of the part and electrode melting (Figure 2) was carried out using calorimetry method.

Influence of exothermal process heat effect, appearing in melting of the electrodes with exothermal mixture in the coating, was experimentally determined by melting the electrodes using reverse polarity direct current at welding current values 290 A and open-circuit voltage of power supply 60 V and statistically analyzed on «Statistica» program.

It is determined that introduction in the electrode coating of exothermal mixture up to 53.4 % (Figure 2, *a*) varies η_p from 0.715 to 0.815 and η_e from 0.28 to 0.415; at that variation is directly-proportional. Increase of amount of deposited metal ($q^{a}_{d.m}$ = 10.5–21.0 g), core being melted ($q^{a}_{m.cr}$ = 14.0–19.0 g) and coating ($q^{a}_{m.c}$ = 8.5–11.4 g) as well as heat power of arc ($\Delta Q_{ia}/Q_{la}$ = 0–12 %) at almost similar amount of

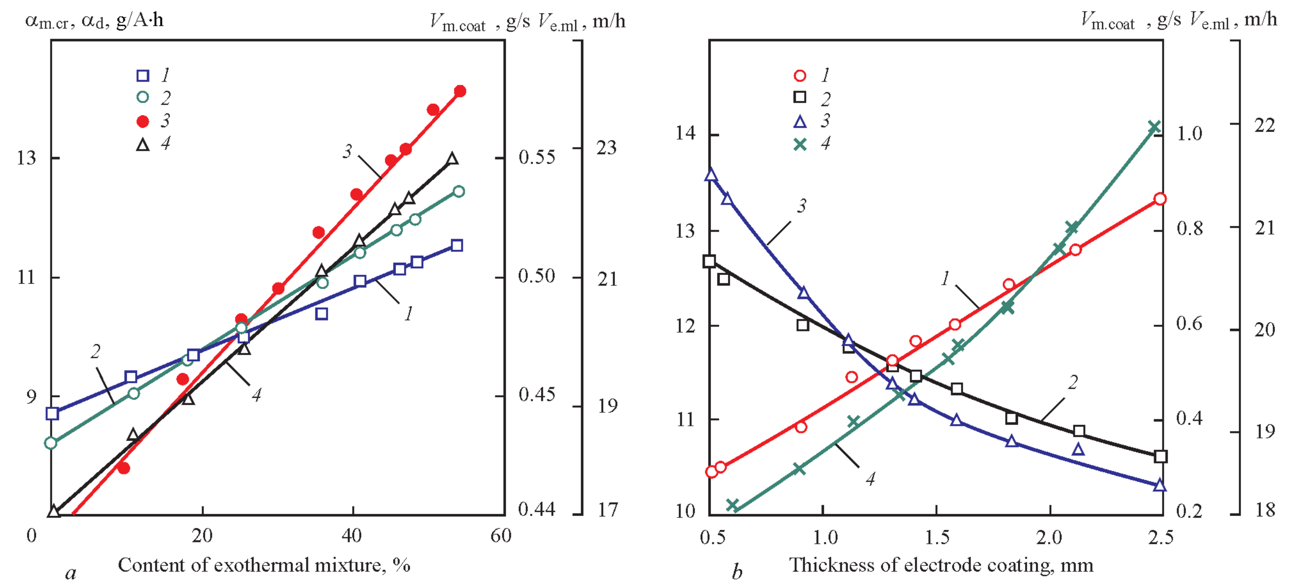

Figure 1. Variation of indices of electrode melting depending on amount of exothermal mixture (*a*) and coating thickness (*b*) in the coating

slag on plate (q^{a}_{sl}) show that additional heating of the plate takes place mainly due to increase of amount of electrode metal per the same time interval and due to increase of arc heat power.

The investigations showed that change of the electrode coating thickness from 0.5 to $2.6 \cdot 10^{-3}$ m (Figure 2, *b*) rises content of exothermal mixture and increase amount of heat and reduced iron during exothermal reaction. Amount of deposited metal and slag on the base metal raised in calorimetry from 17.5 to 21.0 g and from 2.0 to 13.0 g, respectively, that resulted in change of η_p from 0.74 to 0.84; proportional increase of η_e from 0.31 to 0.47, regardless decrease of their melting rate, takes place due to rise of arc heat power and specific heat consumption ($K_e + K_e^{chem}$) for electrode melting.

Despite of reduction of amount of melted core, rise of electrode coating thickness promotes increase of amount of deposited metal that is possible only under condition of intensive reduction of iron from its oxide. Decrease of $\alpha_{m.cr}$ with increase of the coating thickness shows that heat, formed at exothermal reaction, is mainly spent for coating melting that rises its mass rate of melting (0.18–1.03 g/s). Besides, core gives part of heat to the coating that provokes for reduction of core heating and its melting rate. Due to the fact that percent content of exothermal mixture in all investigated compositions of the electrodes was the same, and only its mass amount was varied, we observed just increase of reduced iron from its oxides and rise of efficiency of electrode coating melting.

Due to the fact that increase of exothermal mixture content in the studied electrodes, i.e. metallic compo-

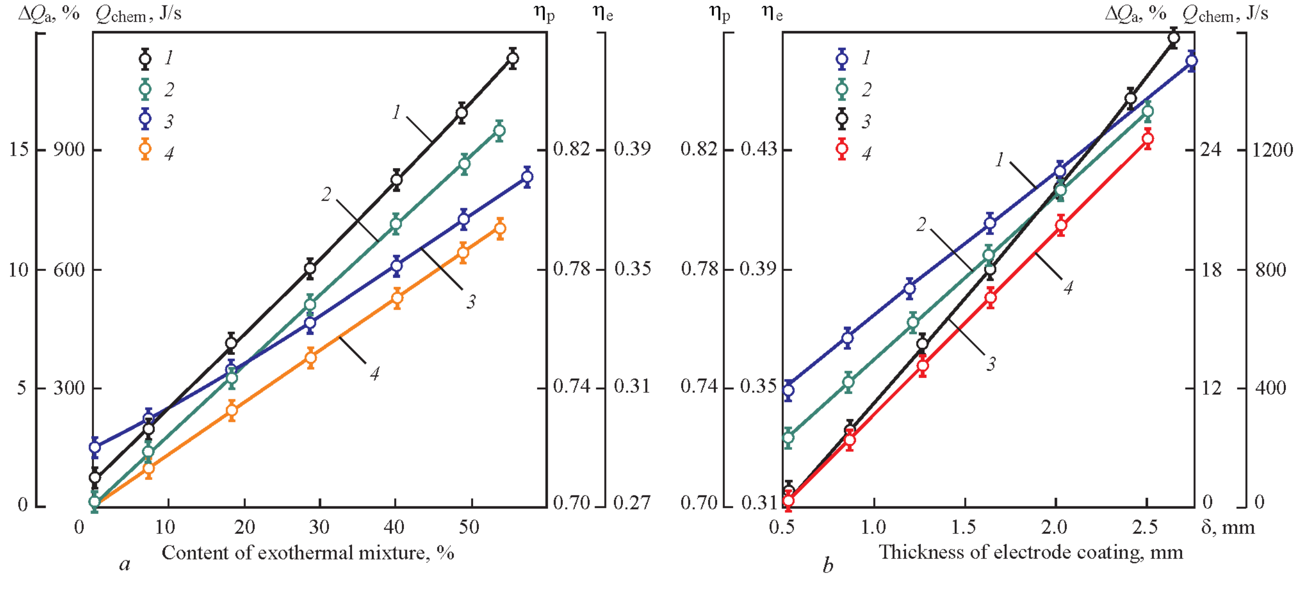

Figure 2. Effect of amount of exothermal mixture in the electrode coating (*a*) and coating thickness (*b*) on melting heat characteristics

nent of the coating, takes place because of respective decrease of content of gas-slag forming part of the coating, then heat expenses for coating melting are reduced, since total heat of iron is lower than that of slag, and portion of heat, spent for core melting as well as droplets heating rises.

It follows from mentioned above that the electrodes with exothermal mixture in the coating are more reasonable for application in surfacing. Deposition coefficient of the electrodes containing 44.4 % of exothermal mixture in the coating makes 11.8–12.5 g/A·h, melting rate 21.5–25 m/h, optimum welding current makes 280–300 A due to increased melting rate and absence of overheating in process of surfacing for electrodes of 5.0 mm diameter.

The statistical models were developed, which allowed determining an optimum content of exothermal mixture and electrode coating thickness. Modelling of the melting process was carried out with the help of software system Statistica 6. The experiments, in which these factors vary at two levels, i.e. experiments of 2^k type, acquired the biggest distribution.

The factors are amount of exothermal mixture Q and coefficient of electrode coating mass K_c. Response is the coefficients of electrode melting $\alpha_{e.m}$, rate of electrode melting $V_{e.m}$ and melting of electrode coating V_{coat} (Figure 3).

Regression equations look like:

$$\begin{aligned} \alpha_m &= 10.55238 + 2.29644K_c - 3.24688K_c^2 + \\ &+ 0.18470Q - 0.00240Q^2 + 0.05875K_cQ, \text{ g/A·h}; \\ V_{e.m} &= (4.68931 - 0.0004K_c + 0.001974Q + \\ &+ 0.000553Q^2 + 0.000057K_cQ)10^{-2}, \text{ m/s}; \\ V_{coat} &= (0.475801 + 0.003526K_c - 0.003735K_c^2 + \\ &+ 0.01418Q - 0.005248Q^2 + 0.000411K_cQ), \text{ g/s}. \end{aligned} \quad (1)$$

The factors are amount of exothermal mixture Q and electrode coating thickness δ_c, Q_{chem}/Q_e. Response is efficiency of part and electrode heating η_p, η_e and relationship of heats Q_{chem}/Q_e (Figure 4).

Regression equations look like:

$$\begin{aligned} \eta_e &= 0.37767 + 0.00594180\delta_c + 0.0083380\delta_c^2 + \\ &+ 0.002299Q + 0.00115Q^2 - 0.04041\delta_cQ; \\ \eta_p &= 0.76075 + 0.94813\delta_c + 0.93457\delta_c^2 + \\ &+ 0.00648Q + 0.00007Q^2 - 0.06425\delta_cQ; \\ Q_{chem}/Q_e &= 9.71120 + 0.4979\delta_c + 0{,}2795\delta_c^2 - \\ &- 0.01102Q + 0.001453Q^2 - 0.01778\delta_c. \end{aligned} \quad (2)$$

Electroslag processes are realized with «solid» or «liquid» start [16].In «solid» start melting of a working flux and formation of the weld pool of necessary volume is carried out in arc mode. The method is characterized with instability (often short-circuitings), non-uniform and continuous flux melting (low efficiency). The electroslag technology for large-sized billets production is performed in bifilar or three-phase type furnaces using only «liquid» start by means of siphon casting of slag melted out of the furnace in lower part of a pocket in electroslag welding (ESW), mold in electroslag remelting (ESR) or casting into crucible in electroslag die casting (EDC). However, laboriousness of ingot casting taking into account time of flux melting in flux-melting furnaces is significantly higher in comparison with «solid» start.

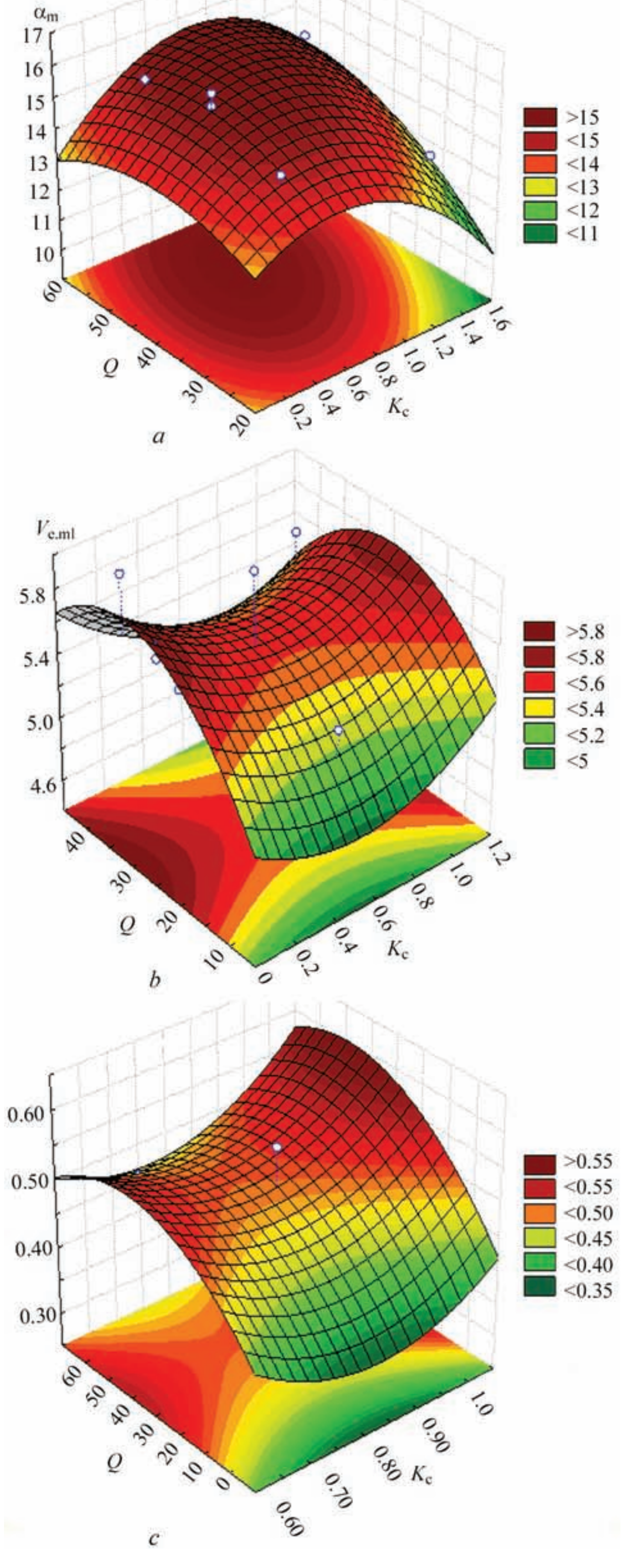

Figure 3. Dependence of melting coefficient α_m (*a*), rate of electrode melting $V_{e.ml}$ (*b*) and electrode coating V_{coat} (*c*) on amount of exothermal mixture Q and coefficient of electrode coating mass K_c

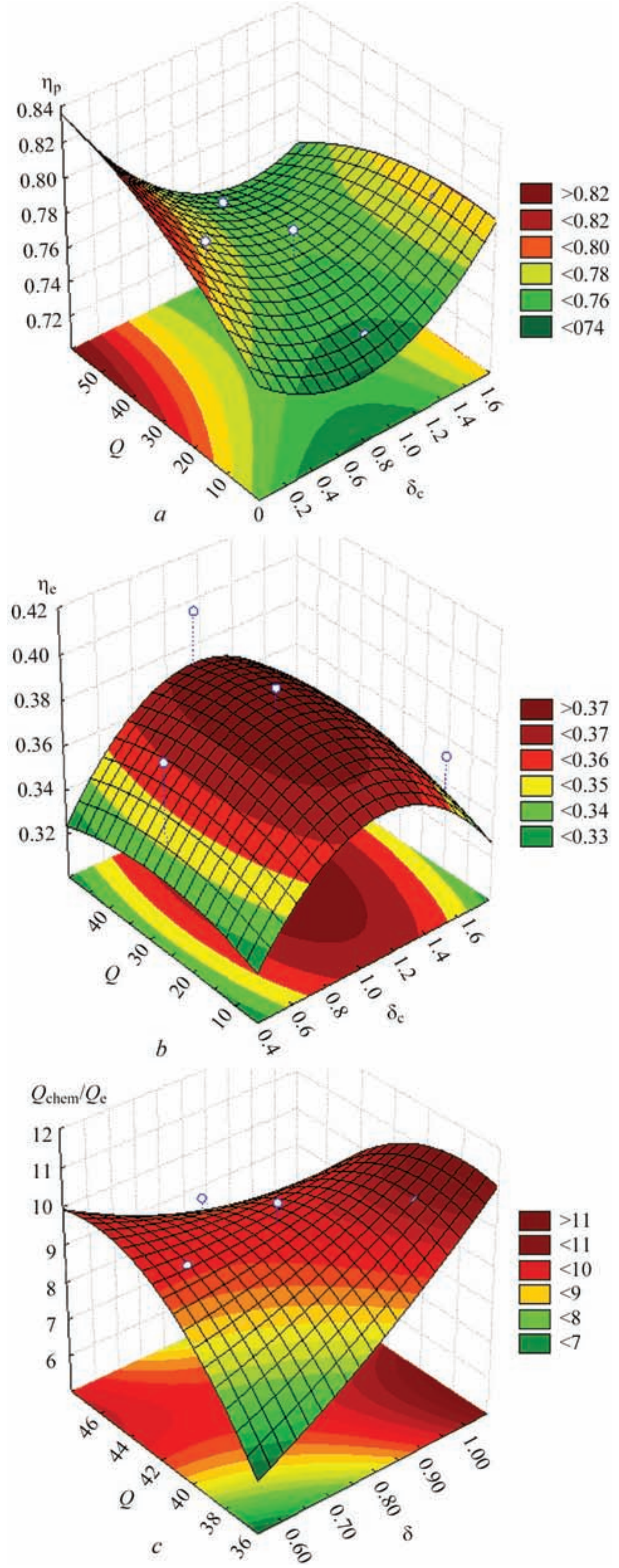

Figure 4. Dependence of heating efficiency of part η_p (*a*), electrode η_e (*b*) and relationship of heats Q_{chem}/Q_e (*c*) on amount of exothermal mixture Q and electrode coating thickness δ_c

An essence of the developed start method lies in the following (Figure 5).

Presence of exothermal mixture in the first (6) and second (5) layers provides for acceleration of working flux melting due to reduction of electric conductivity of the slag and heat emitted at interaction of iron oxides with aluminum. In the first layer (6) exothermal reactions develop temperatures promoting quick melting of the working flux and heating of consumable electrode. Reduction of slag electric conductivity is reached through introduction in the molten flux of aluminum oxide, which is formed due to aluminum to iron oxides interaction. Constant electric mode promotes rise of slag pool temperature, increase melting efficiency and reduction of specific consumption of electric energy. Due to optimum relationship of the components in the first layer (6) it is electroconductive in a solid state and allows complete reaction of aluminum with its oxide formation. Presence of the exothermal mixture in the second layer (5) accelerates its melting without splashes and swirling.

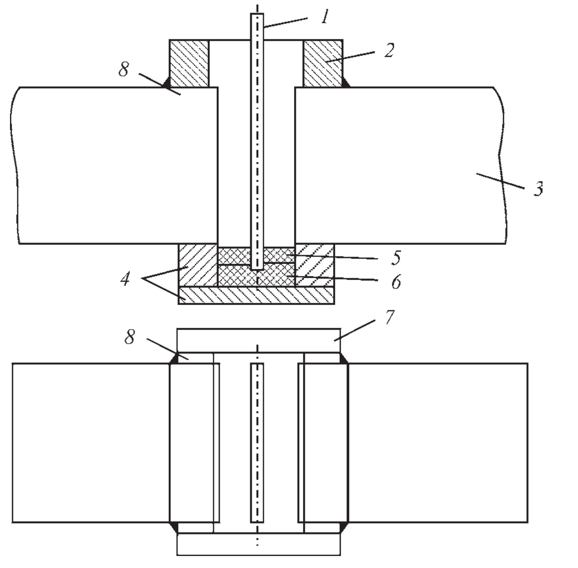

Figure 5. ESW scheme: *1* — plate electrode; *2* — run-off tabs; *3* — welded joint; *4* — metallic pocket; *5* — working flux; *6* — exothermal mixture; *7* — forming backigs; *8* — side plates

Iron is reduced (~70 % of scale mass) in exothermal mixture melting. It precipitates to a bottom plate or dummy ingot and then removed to a crop; refined metal of consumable electrode is deposited over a layer formed from reduced iron and starts formation of sound weld or casting. As the result loss of consumable electrode is decreased to minimum and metal quality in bottom part of the ingot is improved due to that fact that electrode melting takes place in a liquid slag (similar to process with syphon slag casting).

The indices of comparative tests of the optimum variant for developed method of «solid» start and currently applied «solid» and «liquid» ESR starts are given in work [18]. The developed method of ESR start under similar conditions provides for (in comparison with existing «solid» start) 2 times increase of efficiency of flux melting and provide metal yield up to 10 % , reduce by 16 the time of start period for slag pool formation of necessary volume in comparison with existing «liquid» start, and rise by 2 % metal yield. Besides, melting of the exothermal flux forms a slag constituent, namely aluminum oxide (Al_2O_3), mass of which can make to 20–30 % of necessary mass of molten working flux and 1.2–1.4 kW·h saving for melting of 1 kg of standard flux.

Heat effect of the exothermal reaction from interaction of element-deoxidizers with ferrous oxide is determined using the following formula [19]:

$$Q_{\text{chem}} = \sum_{i=1}^{i=k} \frac{G_{\text{m.cr}}}{t} K_{\text{c}} (Q_{\text{зe.m}}) q_{i\text{e.m}}, \ \text{J}/\text{s}, \qquad (3)$$

where $G_{\text{m.cr}}$ is the mass of melted electrode core, g; $Q_{i\text{e.m}} - Q^{\text{Al}}_{i\text{e.m}}$, $Q^{\text{Ti}}_{i\text{e.m}}$, $Q^{\text{Si}}_{i\text{e.m}}$, $Q^{\text{Mn}}_{i\text{e.m}}$ is the portion of exothermal mixture in the electrode coating at interaction of i^{th} element-deoxidizer with ferrous oxide, %; K_{c} is the coefficient of coating mass; $q_{i\text{e.m}}$ are the heat effects (J/g) of exothermal mixture for a reaction of titanium, silicon and manganese with ferrous iron.

Compositions of the exothermal fluxes were developed. They are applied to electroslag processes and provide in their melting conformity of physical-chemical properties of electroslag metal to base metal, electric conductivity in solid state and possibility to carry the processes using mono-, bifilar or three-phase schemes applicable to 9KhF, 9Kh2MF and 60Kh2SMF steels [17, 18].

Conclusions

1. It is proved that an effective method to increase the efficiency of manual arc welding (surfacing) and electroslag processes is application of the exothermal metal-flux mixtures representing themselves mechanical mixture of scale, aluminum powder, alloying elements in form of ferroalloys (ferromanganese, ferrotitanium, ferrosilicium) in manual arc welding (surfacing) and exothermal fluxes («exothermal mixture + standard flux») in electroslag processes in amount sufficient for exothermal reaction.

2. It is determined in experimental way that introduction of exothermal mixture in the electrode coating rises electrode melting rate thanks to heat being emitted in the exothermal reaction (0–11.5 %); provides for reduction of costs for melting of gas-slag-forming part of the coating and improvement of arc process characteristics.

3. It is proved that up to 53.4 % content of exothermal mixture in the electrode coating results in change of efficiency of part heating η_{p} from 0.715 to 0.815 and that of electrode η_{e} from 0.28 to 0.415; at that the change has a direct-proportional nature. Rise of thickness of electrode coating increases content of exothermal mixture; increase amount of heat and reduced iron in the exothermal reaction that results in variation of η_{p} from 0.74 to 0.84 and η_{e} from 0.31 to 0.47 due to increase of arc heat power and specific heat consumptions ($K_{\text{e}} + K_{\text{e}}^{\text{chem}}$) for electrode melting.

4. The statistical models were developed. They allow determining optimum content of the exothermal mixture and electrode coating thickness providing minimum losses of electrode metal.

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