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CONTROL OF THE PROCESS OF BASE METAL PENETRATION AT END FACE ELECTROSLAG SURFACING IN CURRENT-SUPPLYING MOULD*

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In the absence of discrete filler of a certain chemical composition, there appears the task of performing end face electroslag surfacing with large-section electrodes. Here, one of the main surfacing quality characteristics is achieving the minimum and uniform penetration of the base metal. Main principles of design of the system of automatic regulation of these parameters at end face electroslag surfacing in a current-supplying mould were developed. Schemes of control of current distribution in the current-supplying mould are proposed, which allow regulation of the process of electrode melting, and, thus, indirect control of the quality of base metal penetration. A particular scheme should be used to produce a sound bimetal joint with provision of regulation of the position of remelted electrode end face in the slag pool relative to the current-supplying section of the mould and maintaining the calculated heat level of the slag pool. 9 Ref., 7 Figures.

Keywords: *automation, regulation, penetration, end face electroslag surfacing, current-supplying mould, electrode, conductivity*

A method of electroslag surfacing (ESS) in a current-supplying mould (CSM) developed at the E.O. Paton Electric Welding Institute to the largest extent shows its advantages at melting of different type discrete filler materials in a slag pool [1]. Nevertheless, in a series of cases, for example at absence of filler with specific composition, difficulty and high price of its manufacture as well as with the availability of the billets, which can be used for relatively simple manufacture of the remelted electrodes, there is a task to carry out ESS, in particular end face, with large-section electrodes. Moreover, the practice showed that such a method of surfacing under certain conditions allows achieving increased process efficiency with providing its high quality.

Technologies of ESR with canonic electrode-bottom plate monofilar diagram of connection to power source are well studied and in the majority automated [2, 3] in contrast to ESS using end face electroslag surfacing in CSM with upper current-supplying section. One of the main index of surfacing quality is production of minimum and uniform penetration of base metal. This paper is dedicated to development of the basic principles of design of a system for automatic regulation of these indices in end face ESS with large section electrode.

The synergy principles of synthesis [4], stabilizing relationship between the variables of process states are used more often in the recent time for automation of the dissipative systems, to which ESS is referred. Thus, it is possible to achieve degeneration of the dynamic equations of ESS process and presence of integral invariants of manifolds in the space of its states. The invariant manifolds present themselves «some functions, which do not change during movement». Such approaches to automation of the nonlinear objects significantly simplify synthesis of the system. The processes taking place in the mould during electroslag surfacing are determined by number of factors, which in most cases cannot be controlled by operator all the time using the equipment and being evaluated by his/her intuition. Moreover, the level of reliability of such evaluation depends on operator experience. Therefore, for solution of the problem of automation of surfacing process in CSM it is necessary to find the possibility of indirect estimation of the values of parameters, necessary for automation, analyzing electrotechnical processes in the mould and current-supplying circuits.

Large effect on repeatability of the surfacing results can have not only modes and technique of electroslag process itself, but also variation of electrical parameters of the electric circuits out of mould working zone. In particular, length and location of cables influence characteristics of surfacing process. For example, in the case with ESS in CSM of 200 mm diameter at up

*In discussion.

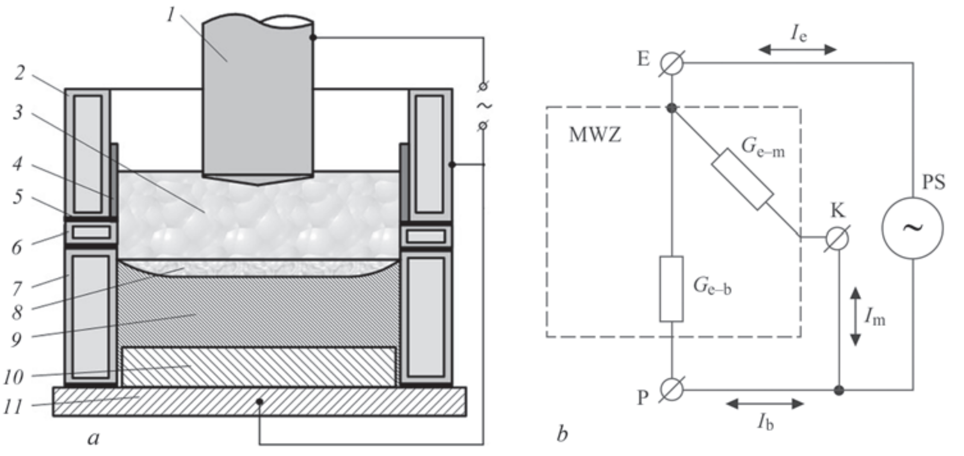

Figure 1. Scheme of ESS in CSM: *a* — with one power source (*1* — electrode, *2*, *6*, *7* — current-supplying, intermediate and forming sections of mould, respectively; *3* — slag pool; *4* — safely lining; *5* — insulating lining; *8* — metallic pool; *9* — deposited metal; *10* — product; *11* — bottom plate); *b* — electric equivalent diagram (PS — power source with rigid characteristic; E, K and P are terminals of electrode connection to current-supplying section of mould and bottom plate, respectively; I_e, I_m and I_b — current passing through electrode, current-supplying section of mould and bottom plate, respectively; G_{e-m} and G_{e-b} — electric conductivity between terminals E and K as well as E and P, respectively)

to 3 kA currents and cable lengths around 10 m the voltage drop at them can reach 15–25 V. Besides, it is necessary to take into account presence of «valve-like effect» in a slag pool [5], which introduces nonlinearity and deteriorates shape of sine wave in connection of alternating current power sources [6, 7]. The same effect shall be considered when selecting polarity of connection of direct current sources to the mould.

Layout of electrical diagram of CSM connection. Figure 1 presents the diagram of ESS in CSM with one power source and its electrical equivalent diagram.

There is a possibility of automatic control of electric parameters of current-supplying elements, which determine a mould working zone (MWZ), i.e. current-supplying section of the mould, slag pool, electrode and bottom plate. It is necessary to measure voltage between the electrode and current-supplying section of the mould U_{e-m}, electrode–bottom plate U_{e-b}, current-supplying section of the mould and bottom plate U_{m-b}, mould current I_m, electrode current I_e and bottom plate current I_b. However, indicated parameters themselves are not representative in order to characterize the process. There is a need in more generalized, complex parameters having higher correlational relationship with processes taking place in the mould working zone, which are «integral invariants of manifolds» of occurring thermodynamic and electrochemical processes in MWZ.

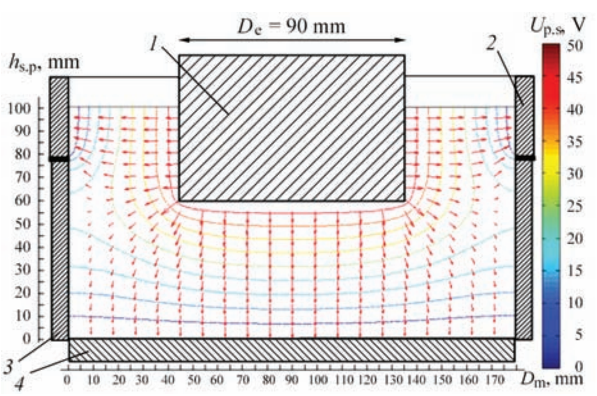

Figure 2. Vector field of electric intensity and field of equipotential surfaces in MWZ; *1* — electrode; *2*, *3* — current-conducting and forming sections of the mould; *4* — bottom plate; D_e — electrode diameter; D_m — mould inner diameter; $h_{s.p}$ — depth of slag pool; $U_{p.s}$ — power source voltage

Independent on connection diagram of the source (sources) to current-supplying elements of the working zone in accordance with Kirchhoff's first law one of the currents (sum current, marked as I_{sum}) will be always determined by sum of two other currents (component currents, marked as I_{com}).

For example, if I_e is I_{sum}, than I_m and I_b are I_{com}. Based on such presentation of electrical connections of inputs and outputs of the working zone it is possible to talk about the parameters, which to some extent characterize the internal processes in the mould, namely this is electrical conductivity of inner channels of the mould working zone along the channels that refer to I_{com}. In our example these are conductivities $G_{e-m} = I_m/U_{e-m}$ and $G_{e-b} = I_b/U_{e-b}$ (Figure 1, *b*). Naturally, that current directions are not considered here and values of currents and voltages are taken by modulus. Figure 2 shows a vector field of electric intensity and field of equipotential surfaces in MWZ in a two-coordinate presentation, obtained by means of electrostatic modelling [8] in PDETool MatLab medium. The image demonstrates division of the electric current flow, passing from the electrode on two passes (conventional inner channels of MWZ) — electrode–current-supplying section of the mould and electrode-bottom plate.

At such interpreting of the inner electrical connections of the elements of surfacing working zone, the mould will be a three-terminal device. If a surfacing diagram with one power source is used, than the mould due to electrical connection of any two (of three) elements (poles) is transformed into a two-terminal device, to terminals of which the source is connected.

Conductivity of conventional «inner» channel of the working zone characterizes a physicochemical state of «channel medium». The «channel medium» is a conventional presentation of the medium, through which current passes between the corresponding inputs/outputs, i.e. current-supplying elements of the mould working zone. Current can pass through the electrode or billet, through slag, through cooled walls of the mould, deposited metal and bottom plate. Conductivity of each of mentioned components of the medium depends on temperature of corresponding parts of the electrode, zones of slag pool and many others. Operator when setting the initial parameters of surfacing such as grades of used consumables, electrode diameter, rate of its immersion into a slag pool and voltage of power source can form the channel medium and, thus, vary nature of its conductivity. At that, change of voltage, applied to the channel, does not change its conductivity in allowably long time duration till the voltage change would not lead to variation of properties of media itself. In turn, introduction into the slag pool of electrode or billet having high conductivity and temperature different from the slag temperature will result in rapid change of pool properties and, thus, change of conductivity of the channels. Thus, in some way it can be assumed that conductivity of the inner channels of the surfacing working zone are the complex parameters characterizing surfacing process in CSM.

Position of the electrode in the slag pool effects the channels' conductivity and, if the temperature of slag is kept constant, relationship of channel conductivities can be indirectly used for estimation of location of end of the consumable electrode in the weld pool. At that, conductivities of the channels can be automatically controlled and regulated for automation purposes. Regulation of electrode feed rate on relationship of channels' conductivity will provide a set location of end of the consumable electrode in the slag pool.

One more of the complex parameters is consumed power. A temperature mode of surfacing process is determined by consumption of power of electric energy applied to the corresponding channel, i.e. for our example $P_{e-m} = I_m U_{e-m}$ and $P_{e-b} = I_b/U_{e-b}$. Regulation of the consumed power allows controlling the temperature mode and efficiency of surfacing process. Automatic control of the consumed power of applied electric energy is possible and variation of the consumed power in both channels to the set value is achieved by change of source voltage. Maintenance of the set relationship of conductivities in both channels and set power of electric energy applied to corresponding channel provides the possibility of quality characteristics of the deposited layer and fusion zone.

Let's consider a diagram for connection of the elements of surfacing working zone presented in Figure 1, *b*. If it is assumed that as a result of multiple experiments it was possible to determined the values optimum for technological purposes of conductivity and consumed power of electrode–mould channel, for example $G_{e\text{-}m}^{opt} = I_m^{opt} / U_{e\text{-}m}^{opt}$ and $P_{e\text{-}m}^{opt} = I_m^{opt} U_{e\text{-}m}^{opt}$, than after small transformations it is obtained $U_{e\text{-}m}^{opt} = \sqrt{P_{e\text{-}m}^{opt} / G_{e\text{-}m}^{opt}}$. So, operator or automatic system should have the possibility in process of surfacing to maintain $U^{opt}_{e\text{-}m}$ value (at that, it is assumed that the electrode feed rate is kept constant at its optimum value). It follows from here that for the purpose of automatic regulation of surfacing process the power source voltage should be smoothly changed in the required limits. Besides, it is necessary to provide control and regulation of electrode displacement at stationary mould or, vice versa, mould at stable electrode, with sufficient accuracy and in the necessary range to maintain $U_{e\text{-}m}^{opt}$ in accordance with the technological requirements.

It is supposed that for the specific set initial conditions of surfacing there is a single optimum solution on variation in time of electrode displacement rate as well as corresponding solution on change in time of source voltage (in set time interval). As a result of realizing such a solution it is possible to reach predicted quality of surfacing with the set values of deposition rate and energy efficiency. Search of indicated «optimum» solution should be preformed by a control system using automatic collection of data on each surfacing.

It is possible to formalize types of channels in the working zone following the ideas on the mould working zone. There are three types of diagrams of surfacing working zone channels in CSM (Figure 3), marked as «E», «K» and «P». They differ by location of common terminals of the working zone (common terminal corresponds to input/output, on which sum current I_{sum} is passing). In this interpretation the channel of surfacing working zone in CSM is a pass between the elements of this zone connected by resistor. Resistor conductivity is a channel conductivity.

Due to the fact that there are three current-supplying elements in the working zone, then number of variants of power source connection also makes three

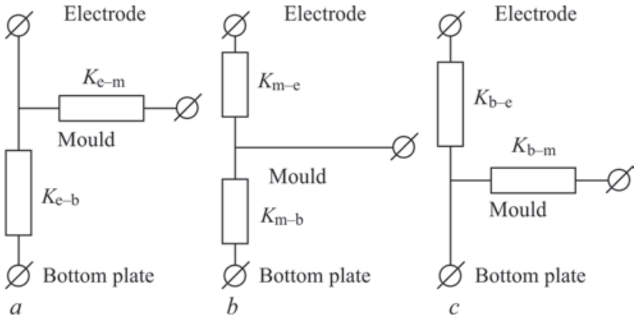

Figure 3. Types of diagrams of surfacing working zone channels: *a* — «E»; *b* — «K»; *c* — «P» (K_{e-m} — «electrode–mould» channel; K_{e-b} — «electrode–bottom plate»; K_{m-e} – «mould–electrode»; K_{m-b} — «mould–bottom plate»; K_{b-e} — «bottom plate–electrode»; K_{b-m} — «bottom plate–mould»)

since the source is connected to a pair of zone elements. There are only two variants for connection of remaining third terminal, namely to one or to another source terminal. Figure 4, as an example, shows the diagrams for connection of elements of working zone to alternating current power source. The diagrams for connection to direct current source are similar.

Thus, three variants of diagrams for connection of source to mould are proposed. The most perspective for increase of surfacing efficiency is «E» type diagram and, in less degree, «K», since the experience shows that the best melting of the electrode takes place at sufficiently high currents, passing through the electrode and mould, thus providing high process efficiency. In contrast to a diagram of type «P», which is characterized by high current passing through the bottom plate, small rate of electrode melting, but good and uniform penetration of the base metal.

Therefore, when choosing a diagram for connection of source to current-supplying elements of the working zone, it is necessary, first of all, orient on selection of type of channel diagram, i.e. on that which terminals shall be short-circuited. Geometry of the working zone of mould in many aspects determines this choice.

The following functions are taken as one being automated for the first stage of system development:

• function of selection and maintain of electric mode for formation of fusion of dissimilar metals with set relative nonuniformity of penetration and minimum average penetration depth;

• function of selection and maintain of electric mode for providing stable conditions of deposited metal solidification.

Selection of that or another electric mode is carried out by operator from the list provided by the system. The system is designed in such a way that a story of surfacing was collected and stored in computer memory. From the information in computer memory the operator can select necessary mode or develop new with further storage. After mode is selected and system launched «into operation», the system stabilizes the set parameters in a set range. The values of set parameters and range of stabilizing are not constant and being determined by selected mode.

Automation of mode of fusion formation between dissimilar metals with set relative nonuniformty of penetration and minimum average penetration depth requires stabilizing the set value of electrode deepening and set voltage of source in connection of source to CSM on diagram «P».

Automation of stable conditions for deposited metal solidification requires stabilizing the set value of conductivity of electrode-bottom plate channel and set voltage of source during connection of source to CSM on diagram «E».

Such an approach of electroslag surfacing was proposed in work [9] based on evaluation of longitudinal sections of bimetal billets.

Conceptually, the following functions and problems shall be fulfilled in development of a system for automatic control of ESS in CSM:

• control and indication of current values of rate of consumable electrode displacement, voltage of power source, surfacing currents passing through the electrode, mould and bottom plate;

• providing the devices setting the values of mode parameters, indication of set typical surfacing mode;

• control and indication of values of calculated parameters (value of electrode deepening, deposition rate, time of process etc.);

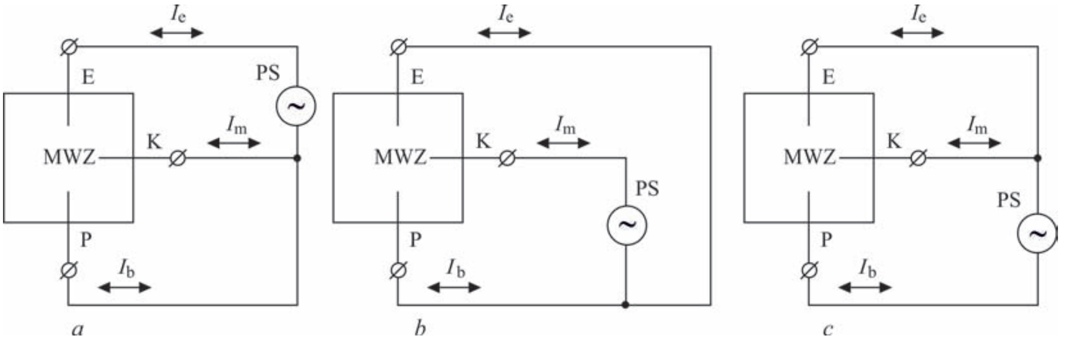

Figure 4. Types of diagrams for connection of elements of surfacing working zone to alternating current power source: *a* — «E»; *b* — «K»; *c* — «P»

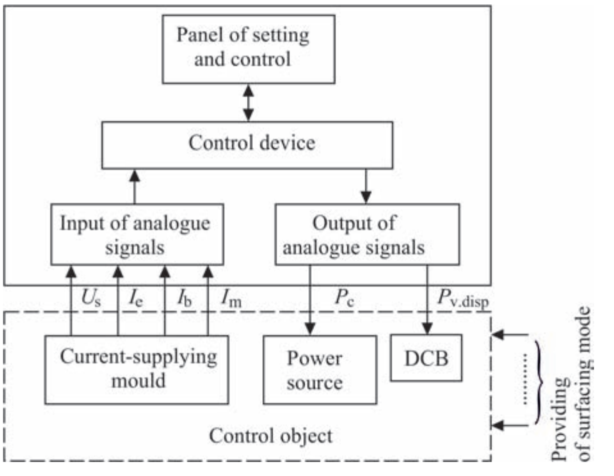

Figure 5. Structural scheme of automation of base metal penetration in ESS in CSM

- mathematical modelling and experimental researches of dependencies of depth and uniformity of penetration on value of electrode deepening and power consume by current-supplying mould;
- automatic control of electrode displacement;
- automatic control of voltage, current and power consumed by surfacing.

Structural scheme of automation of base metal penetration during ESS in CSM is presented in Figure 5. The system consists of a block of «Input of analogue signals» designed for entry into the system of signals of surfacing voltage U_s and currents I_e, I_b, I_m, i.e. electrode, bottom plate and mould, respectively, coming from probes located in the immediate vicinity to «Current-supplying mould». Block for «Output of analogue signals» is designed for output of the controlling signals P_c — controller of output voltage of «Power source» and $P_{v.disp}$ — controller of displacement rate of consumable electrode, which influences a drive control block («DCB») of electrode displacement mechanism. «Panel of setting and control» is designed for manual entry and indication of discrete, digital, text information and automatic input of indicated information in «Control device» as well as obtaining from it the signal for indication on «Panel of setting and control» itself. «Control device» obtains the analogue signals from «Control object» and discrete signals from «Panel of setting and control», performs mathematical processing of these signals and forms the discrete signals for transfer into «Panel of setting and control» for indication as well as the controlling analogue signals for «Control object». Besides, it records a history of surfacing for unstudied types and modes of surfacing for the purpose of further processing of recorded information files and modernizing system software, forms an array of approximating regression functions for types and modes of surfacing provided in the system as well as an array of surfacing history.

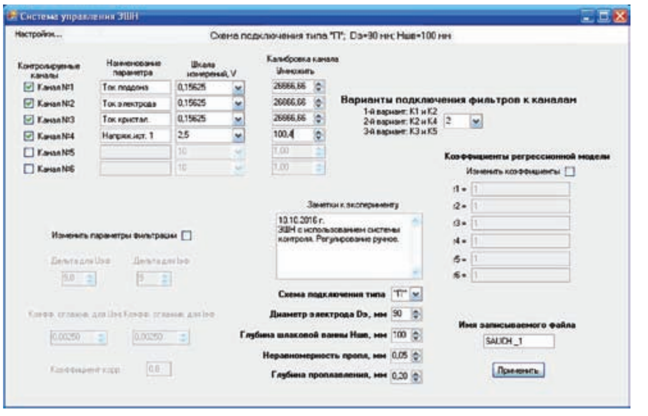

Figure 6. Appearance of computer screen at initial setting of ESS control system before surfacing

At this stage the «Control device» is realized based on notebook LENOVO model IdealPad Y560 with 64-bit operating system. Input of analogue information is carried out using external ADT E14-140-M L-CARD (bus USB2), which is in particular conformable for development of portable measuring system based on notebook. It has software controlled setting of the parameters for data collection, namely amount and sequence of input channels' inquiry, measurement range, frequency of analogue-digital transducer. An original non-standard device of own design is used as normalizing transducers of current and voltage signals.

«Manual» regulation was carried out using the indices calculated by the system. Manual mode was used to maintain a rate of electrode feed for the purpose of stabilizing the value of electrode deepening into the slag pool as well as value of power voltage.

Figure 6 presents a view of computer screen at initial setting of the ESS control system before surfacing. Parameters of entering and filtering the input signals, technological conditions of subsequent surfacing, type of diagram for connection of source to CSM etc. are set.

Figure 7 presents a view of computer screen during system operation in mode of control, regulation and registration of surfacing process. The values of source

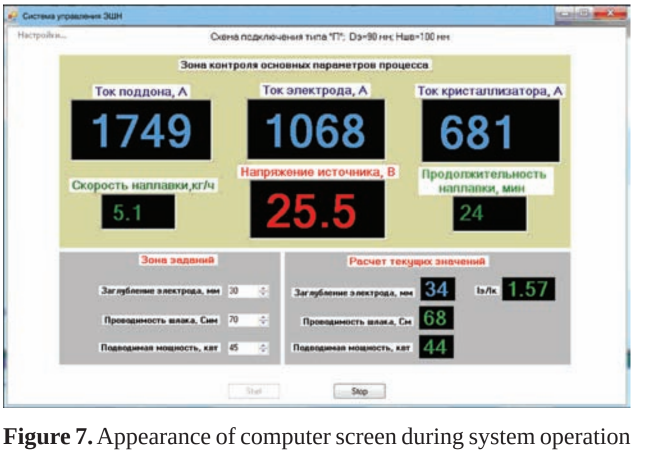

Figure 7. Appearance of computer screen during system operation in control mode, regulation and registration of surfacing process

voltage, currents of bottom plate, mould and electrode are displayed on the screen in real time mode with frequency of presentation 1 Hz. A rate of surfacing and duration of surfacing are presented with 1 min period. Calculated current values of process parameters are displayed with 5 s period.

Conclusions

1. Developed were the main principles of design of the system for automatic regulation of base metal penetration in end face electroslag surfacing with large-section electrodes in current-supplying mould. A pilot version of computer system for automatic control of ESS in CSM was developed.

2. Based on the presentations of the mould working zone, technologist can choose among three proposed diagrams of current distribution in surfacing working zone, titled as «E», «K» and «P», which determine the process of electrode melting and value of base metal penetration.

3. Determined were the main controlled complex parameters in the system, i.e. electric conductivity of the channels and power consumed by them. Using them it is possible in indirect way to determine position of the end face of consumable electrode in the slag pool and regulate the process of electroslag surfacing varying the rates of electrode deepening and voltage of power source. It will result in providing the minimum and uniform penetration of the base metal, stabilizing the surfacing process with the set values of productivity and energy efficiency.

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