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STABILITY OF THE PROCESS OF ELECTROSLAG WELDING WITH BIFILAR POWER CIRCUIT WITHOUT EQUALIZING WIRE

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Electroslag welding (ESW) by wire electrodes with bifilar circuit of power connection without equalizing wire is not applied now. There is reason to believe that bifilar ESW without the equalizing wire has certain advantages over bifilar electroslag remelting (ESR) without equalizing wire. Therefore, additional studies of the process of bifilar ESW without equalizing wire are required. Investigations were performed and the range of parameters of a stable process of ESW with bifilar power circuit without equalizing wire was determined, using a mathematical experiment. The causes for process unbalance can be temporary violation of the feed rate of one of the electrodes, local change of electrode cross-section, asymmetrical arrangement of the electrodes in the slag pool, etc. The notion of "resistance to external factors (REI) was introduced. It was proposed to use as the measure of resistance, the maximum value of REI parameter, above which the process goes into an unstable mode. REI nomogram was obtained, depending on welding voltage and electrode feed rate, which allows selection of the mode of bifilar ESW with the highest resistance to external disturbances. A mathematical model was used to show that the process of bifilar ESW without equalizing wire can run in a stable manner in a certain zone of values of the technological mode parameters.

KEY WORDS: electroslag welding, bifilar circuit, slag pool, metal pool, electric conductivity

INTRODUCTION

In 1960s PWI developed a new process of electroslag remelting (ESR) — so-called bifilar electroslag remelting. The essence of the process consists in that in a bifilar furnace two consumable electrodes are connected is series to the secondary winding of a single-phase transformer. It was proved that bifilar electroslag remelting has more advantages over the canonical two-electrode monofilar ESR [1], as the units operating by this scheme consume less power, are more efficient and have a higher power factor. Their advantages are especially great in production of slab ingots and plate ingots. However, alongside the advantages (such as favourable position of the zones of the main heat evolution in the slag pool, reduction of reactance of furnace loading), a bifilar ESR furnace without equalizing wire turned out to be operationable only in a certain range of remelting modes, as a result of ineffective self-regulation. That is, the process became unstable at certain short-term external distances acting on it. To eliminate this drawback with preservation of ESR bifilar circuit advantages, the secondary winding of the supply transformer is made with a midpoint, connected to the workpiece to be welded by equalizing wire.

As regards bifilar ESW with wire electrodes without equalizing wire, such a technology has not been used up to now. There is ground to believe that bifilar ESW without equalizing wire has certain advantages over bifilar ESR without equalizing wire. As the sectional area of consumable electrodes in ESW and ESR differs considerably, the thermophysical processes causing their melting also differ essentially. Analysis of the pattern of current spreading in the slag pool of ESR bifilar furnace without equalizing (zero) wire [1] was performed by a simplified two coordinate (2D) electric circuit. Here, current spreading along the workpiece edges and shoes was not taken into account. The proposed ratio of current flowing through the slag and the metal pool (10–30 %) and current, flowing only between the electrodes in the slag pool (90–70 %), requires more precise determination in 3D dimension. Therefore, additional studies of the process of bifilar ESW without equalizing wire are required. New data will result in corrections in the range of parameters for a stable ESW process.

The objective of this work is study and determination of the parameter range of a stable process of ESW with bifilar power circuit without equalizing wire, using mathematical experiment.

The mathematical experiment was performed with application of an earlier developed model [2]. In the mentioned work mathematical experiments were conducted with two-electrode ESW, connected to a power source by monofilar and bifilar circuits with equalizing wire. In order to study the distribution of the electric field, current and potential in the slag pool, workpiece being welded, the forming weld, and the shoes, as well as heat distribution in the studied zone volume, its finite element model was used, which consisted of a slag and metal pools, two shoes, two electrodes, immersed into the slag pool, as well as fragments of the workpiece and the weld. In connection with the fact that the circuit of welding equipment connection to the power source creates external conditions for the model and does not change either graphic, or physical characteristics of the model of the studied ESW zone, a decision was taken to use this model for conducting a mathematical experiment in the study and determination of the parameters of a stable ESW process with bifilar power circuit without equalizing wire. Here, the cables of the transformer secondary winding are insulated from the grounding terminal of the power source. ESW power supply circuit is shown in Figure 1.

With bifilar power circuit of ESW without equalizing wire, the current in the slag pool flows in two generalized circuits: "electrode e1 – slag pool – electrode e2"; "electrode e1 – slag pool – workpiece – slag pool – electrode e2". It is understood that the current flowing in the workpiece, is the current passing through the metal pool, workpiece edges and shoes. The current in each of the above-mentioned circuits depends on their electric conductivity, which, in its turn, depends on the flux composition, used metal grades, as well as on the temperature state of each elementary volume of this zone of the welding process, through which the current flows. The potential of both the workpiece edges, shoes, weld and metal pool is of practically equal importance, in view of their low specific resistance, compared to higher specific resistance of the slag pool. More over, for the purpose of electrical safety of service personnel, the ESW unit and the workpiece are grounded.

At the change of ESW supply voltage and/or rate of electrode feeding into the slag pool, the depth of electrode immersion and their melting rate are also changed. Here, the conductivity of each of the above-mentioned circuits and the distribution of the amount of heat, evolving in the slag, are changed. In connection with the fact that the same current flows in both the electrodes in the bifilar circuit, a feedback forms between the processes of self-regulation of melting rate of each of them. Therefore, for the bifilar circuit it is important to maintain a balance between the electrode melting rates, as the change of self-regulation feedback in the electrodes from the negative to the positive one can lead to instability of ESW process. The causes for the unbalance can be temporary violation of the feed rate of one of the electrodes, local change of electrode section, asymmetrical arrangement of the electrodes in the slag pool, etc. Figure 2 gives an example of asymmetrical running of ESW process.

In order to understand the nature of the change of electrical characteristics of the electroslag process

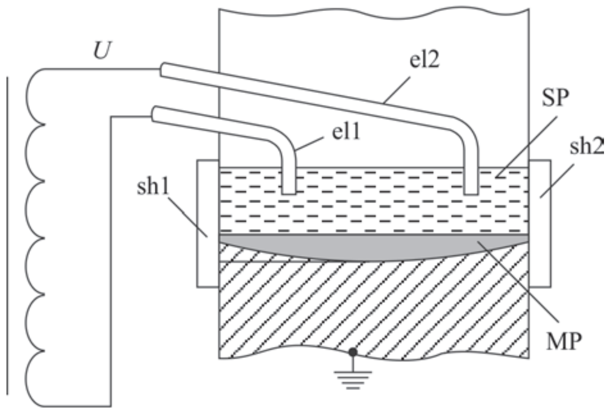

Figure 1. ESW two-electrode bifilar power circuit without equalizing wire (U — power source voltage; e1 and e2 — consumable electrodes; sh1 and sh2 — water-cooled shoes; SP, MP — slag and metal pools)

when different disturbances are introduced into it, for instance, at the change of the rates of electrode feeding into the slag pool, a physical experiment on bifilar ESR into a graphite casting mould was conducted in the laboratory conditions at PWI using AD-381Sh machine [3]. Remelting was performed with bifilar circuit of power source connection without equalizing wire with a grounded stand. Technological parameters of experimental remelting were as follows: mould internal dimensions of 80×30 mm, electrode spacing of 40 mm (at symmetrical arrangement of the electrodes relative to each other); slag pool depth of 50–70 mm; electrode wire diameter of 3 mm; number of electrodes — 2.

The testing objective was to perform continuous saving on electronic carrier of such parameters as feed rate of electrode e1 – V_{f1}, feed rate of electrode e2 – V_{f2}, voltage between the nozzle of electrode e1 and workpiece U_1, voltage between the workpiece and nozzle of electrode e2 – U_2, as well as power source current I_w, while changing the feed rate of electrode e2 in a certain range during the remelting process (at

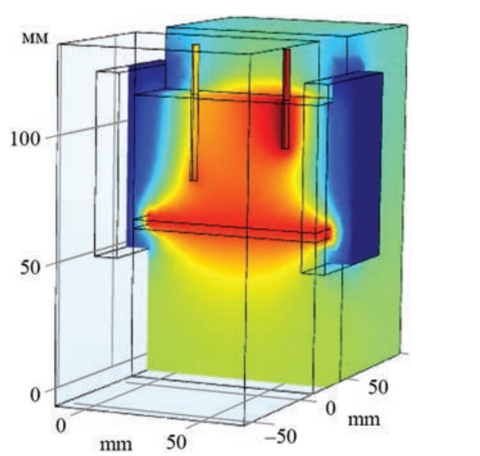

Figure 2. Fragment of the graphic part of the model (sectional view) at the developed asymmetry of ESW process

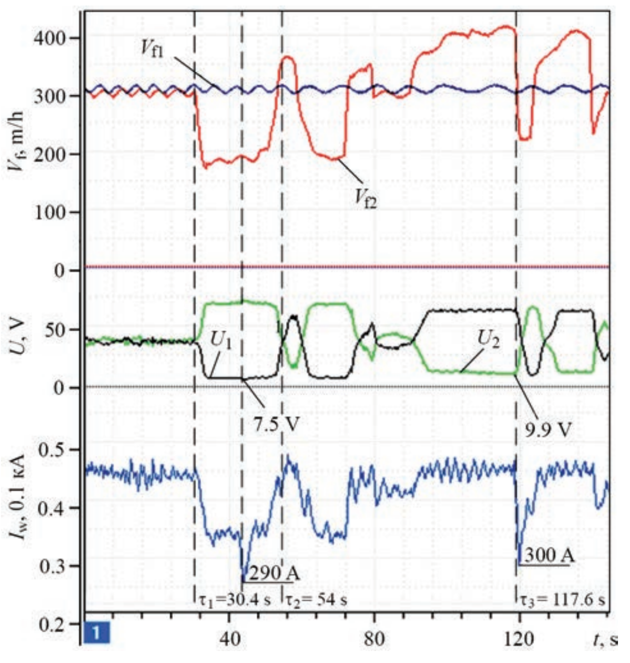

Figure 3. Dependencies of the change of ESW parameters in time with simulation of external disturbances

unchanged feed rate of electrode e1) at supply voltage $U = 85$ V (Figure 3).

One can see in Figure 3 how the voltage between the electrodes and workpiece U_1 and U_2 changes at the change of V_{f2}. The sum of these voltages is equal to power source voltage of 85 V. In the range of $\tau_1 - \tau_2$, V_{f2} is smaller than V_{f1}, resulting in shallower immersion of electrode e2 (Figure 2), lower conductivity of "electrode e2 – workpiece" channel, lower power source current, and higher voltage U_2 between electrode e2 and workpiece. Voltage between electrode e1 and workpiece $U_1 = U - U_2$ decreases accordingly. In this time range at low V_{f2}, voltage U_1 reaches a critically small value of 7.1 V. Here, electrode e2 reaches minimum immersion into the slag pool and current I_w drops abruptly from 350 to 290 A. A similar situation is observed at moment of time τ_3, when electrode e1 reaches a minimum of immersion into the slag pool at critical value of voltage $U_2 = 9.9$ V. Here, current I_w drops abruptly from 460 to 300 A.

This physical experiment showed that violation of the process stability can occur at certain combinations of the values of electroslag process parameters and external disturbances. For a technologist, developing the melting process, it is important to know the working zone of parameter values and the level of process resistance to external disturbances. We will introduce the notion characterizing the electroslag process with bifilar power circuit without equalizing wire — "resistance to external factors". It is recommended to use as the measure of resistance, the maximum value of REI parameter, above which the process goes into unstable mode. REI is determined as follows:

$$\Delta U = \left|U_1 - U_2\right|; \text{ rei} = \left|\frac{\Delta U}{U}\right| \cdot 100\,\%,$$

where rei is the intermediate value of the external factor, %; REI = max (rei) is the limit of the mode of stable running of the process. A stable mode is found in the range of $0 \le \text{rei} < \text{REI}$.

At bifilar ESW any external action, leading to unbalance of electrode melting rates, always leads to value $\Delta U > 0$. Therefore, in the computational experiment the unbalance can be assigned in the model by changing ΔU, as a source of unbalance, which is universal.

For the computational experiment the following model parameters were taken: $U = 85$ V; $V_{f1} = 280$ m/h; workpiece thickness of 80 mm; gap width of 30 mm; slag pool depth of 50 mm; electrode spacing of 40 mm; workpiece material was 09G2S steel; electrode wire was Sv.08G2S steel; flux was AN-8; forming shoes were from copper. Physical properties of the materials are given in the Table 1 [4].

Parameters $C\rho[T]$, $\rho[T]$, $k[T]$, $\alpha[T]$, $\sigma_{st}[T]$, $\sigma_{sh}[T]$ were set by the respective approximating dependencies on temperature T, K (not given in the paper).

Computational experiment yielded maximum values of short-term disturbance. The limit was found, at which the feedback between the processes of self-regulation of melting rates of both the electrodes changes from the negative to positive one (Figure 4).

Maximum value of disturbance, above which the process goes into an unstable condition, is equal to $\Delta U = 14.4$ V. At $U = 85$ V the stability value should be:

Table 1. Physical properties of materials used in the model

Parameter	Workpiece	Electrodes	Slag	Shoes	Weld
Heat capacity ($C\rho$), J/(kg·K))	Cρ[T]	Cρ[T]	1400	385	Cρ[T]
Relative dielectric permeability (ε)	1	1	2.5	1	1
Density (ρ), W/(m·K)	ρ[T]	ρ[T]	2600	8960	ρ[T]
Thermal conductivity (k), W/(m·K)	k[T]	k[T]	295	400	k[T]
Thermal expansion coefficient (α), l/K	α[T]	α[T]	-	17E-6	α[T]
Specific electric conductivity (σ) S/m	σ_{st}[T]	σ_{st}[T]	σ_{sh}[T]	6E7	σ_{st}[T]

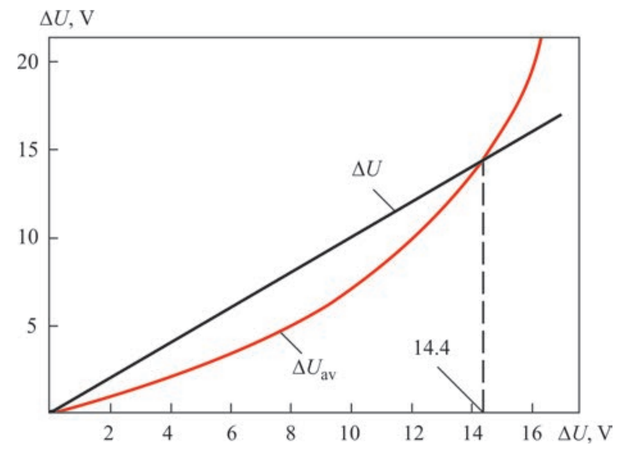

Figure 4. Result of self-regulation of electrode melting rates (ΔU — disturbance value, V; ΔU_{av} — respective reaction of the process as a result of self-regulation of electrode melting rates, V)

$$\text{REI} = \frac{14.4}{85} \cdot 100\,\% = 19.9\,\%.$$

At long-term action of an external factor, the value of which is smaller than REI, the process will go into a stable mode with different depth of electrode immersion into the slag pool, leading to thermal field asymmetry and may lead to violation of the uniformity of workpiece edge penetration.

The created model was used for computation of REI for different combinations of U and V_f values. REI = $F[U, V_f]$ nomogram was derived (Figure 5), which allows selection of the mode of bifilar ESW without equalizing wire with the highest resistance to the action of external disturbances. During REI computation, the following constraints were set for the model, at which the process of bifilar ESW should, probably, be more stable:

- temperature of lower electrode faces does not go beyond 1500–2000 °C;
- electrode immersion depth stays within 2–48 mm;
- presence of negative feedback between the processes of self-regulation of both the electrodes is mandatory.

Study of the conditions of current spreading in the slag pool and the workpiece, conducted using the model, showed that, depending on ESW mode (voltage, electrode feed rate, welding zone geometrical parameters, electrode arrangement in the slag pool) from 33 to 85 % of current flows between the electrodes through the slag pool, while the other part of current (15–67 %) passes through the slag and the workpiece, including the shoes. It leads to the assumption that for modes of bifilar ESW without equalizing wire, characterized by considerable currents, flowing through the workpieces, the influence of feedback between self-regulation of each of the electrodes will be reduced, and it will allow

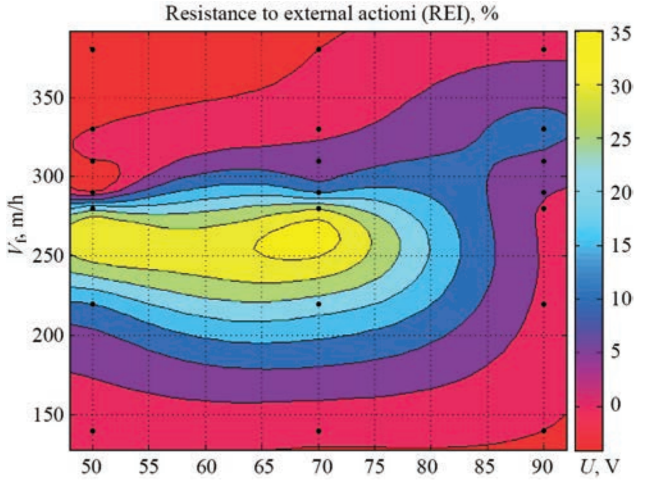

Figure 5. Nomogram of resistance of bifilar ESW process

widening the range of ESW process stability. It can be the subject of further studies.

CONCLUSIONS

1. For ESW bifilar circuit it is important to keep a balance between the processes of melting of both the electrodes. The causes for unbalance can be temporary violation of feed rate of one of the electrodes, local change of electrode cross-section, asymmetrical arrangement of electrodes in the slag pool, etc.

2. The notion of "resistance to external factors" for bifilar ESW without equalizing wire was introduced. As the measure of resistance, it is proposed to use the maximum value of REI parameter, above which the process goes into an unstable mode.

3. REI nomogram depending on welding voltage and electrode feed rate was derived, which allows selection of bifilar ESW mode with the greatest resistance to the action of external disturbances.

4. Using the mathematical model, it was shown that the process of bifilar ESW without equalizing wire can run in a stable manner in a certain zone of technological mode parameters.

5. The developed model can be used to predict the parameters of a stable process of bifilar ESW after physical model testing.

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CONFLICT OF INTEREST
The Authors declare no conflict of interest

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