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PECULIARITIES OF ELECTRODE AND BASE METAL MELTING IN ELECTROSLAG WELDING

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Results of experimental studies of the connection between the processes proceeding in the electrode wire melting zone and electric parameters of the electroslag welding mode are described. The experimental procedure envisaged electroslag welding of specimens from 60 mm thick steel 09G2S the in modes identical to those, used earlier for photographing and filming the welding zone through an optically transparent medium. Hall sensor, ADC module E-140 and «Power Graph» software were applied for high-speed recording of electric parameters of mode (10 thou records per second). Measurements of slag pool temperature near the electrode wire melting zone were taken simultaneously. Analysis and comparison of visual observations of the welding zone through an optically transparent medium with the characteristics of electroslag welding mode (U_w, I_w, $V_{w.f}$) were performed, confirming the cyclic existence of some nucleus in the molten slag between the electrode wire and liquid metal, formed under the effect of electric potential between the base and electrode metal. 9 Ref., 4 Figures.

Keywords: *electroslag welding, slag pool, interelectrode gap, high-speed recoding of electric parameters of mode, active zone, energetic nucleus, «discharge», melting and transfer of liquid metal, high-speed photographing and filming*

Electroslag welding (ESW) is one of the types of fusion welding and is based on use of heat energy released during electric current passing through the molten flux. This process has a number of specific characteristics which determine the priority and scope of its application in different branches of the national economy in welding metal of 40 mm thickness and larger in one pass [1].

Studying the physical nature of ESW will not only allow improving the efficiency of the welding process control to optimize sizes of the weld and penetration depth of the base metal, but also finding the ways to reduce heat input in welding zone for decreasing the volume of subsequent heat treatment of welded joint metal necessary for recovery of high service characteristics of a welded structure.

Therefore, the studying of processes, proceeding in interelectrode gap when performing ESW, was always relevant. However, often, due to the present demands in the welding industry, the mentioned study was inferior to solving practical problems in the development of welding technologies for specific metal structures of heavy machine building, hydropower engineering and other industries.

From the beginning of the electroslag welding process development, researchers were striving to look into the welding zone. The primary ideas about the processes occurring in the slag pool were obtained using the methods of indirect observation and described in the works [2–6]. The first information about the shape of melting electrode and interelectrode gap was obtained by G.Z. Voloshkevich [2, 3]. However, due to a number of technical reasons, the obtained results did not allow studying the dynamics of processes proceeding in the interelectrode gap.

Later, the authors of works [7, 8] managed to carry out a more successful direct observation of the ESW process and its high-speed filming by conducting the specially prepared experiments using heat-resistant glass, which was installed instead of a copper water-cooled shoe.

It is known that the phenomena, observed in the welding zone, arise in the process of conversion of electric energy into heat one (electric parameters of the welding mode). Their character also depends on the physicochemical properties of the slag pool and electrode material.

According to the literature data [1–3, 9], the heating and melting of the wire electrode occurs in the area of an active contact of its surface, which is moistened with slag. The area of this surface is variable and depends on the welding mode parameters (values of voltage on slag pool, welding current, diameter and electrode feed speed, slag pool depth, etc.). For the established ESW processes used in practice, the contact surface area can vary in the wide ranges, for example, for wire with a diameter of 3 mm it is 14–110 mm^2 [9]. The molten electrode metal of the wire flows along its side surface into the gap between the electrode end and metal pool. As a result of computer processing of filming frames of the slag pool, its typical regions were distinguished: the zone of the highest temperatures, which has a direct contact with the electrode end, and the zone, whose temperature is lower than that of the mentioned one, but higher than that in the volume of a slag pool [9].

The results of investigation of the process of electroslag welding with a wire electrode through the optically transparent medium confirmed the known basic definitions of the physical principle of this process [1], and also allowed developing the ideas about the phenomena occurring in the active zone of the slag pool, on which melting of base metal and weld formation depend [9].

On the basis of direct visual observations of the welding zone, the existence of some energetic nucleus was shown, formed under the action of electric potential between the base and electrode metal in the welding zone, in the molten slag between the end of the electrode wire and the metal pool.

During investigation and analysis of the welding mode characteristics, the following regularities were recorded:

• cyclic (with a duration of 0.3–0.6 s) nature of variation in sizes of this nucleus;

• increase in the critical state of energy characteristics of the nucleus before the end of the cycle;

• it is shown that the concept of the metal pool depth, usually defined by macrosections, does not correspond to its actual instantaneous parameters.

At the same time, it was suggested that the «explosive» change in the energy characteristics of the region between the electrode wire end and the metal pool before finishing the cycle occurs during the formation of slag vapors. During the transition of a slag from a liquid to a vapor-gas state, this region grows in volume in a very short time with the rise in conductivity and slag vapor temperature, reaching the maximum degree of ionization of the interelectrode gap, increasing the pressure, which together leads to explosive completion of the cycle.

With a decrease in the interelectrode gap due to slag evaporation, a «discharge»* occurs, in the volume of which the pressure and evolution of heat energy increase. The pressure of the «discharge» is transmitted to the metal pool and the entire volume of slag in a pulsed mode by means of electrohydrodynamic shocks, causing intensive heat flows in the metal and slag pools. Under the action of these flows, the edges being welded are fused and the slag pool is heated [9]. The given results of the investigations were obtained by studying the visual phenomena in the slag pool without a corresponding recording of the welding mode electric parameters.

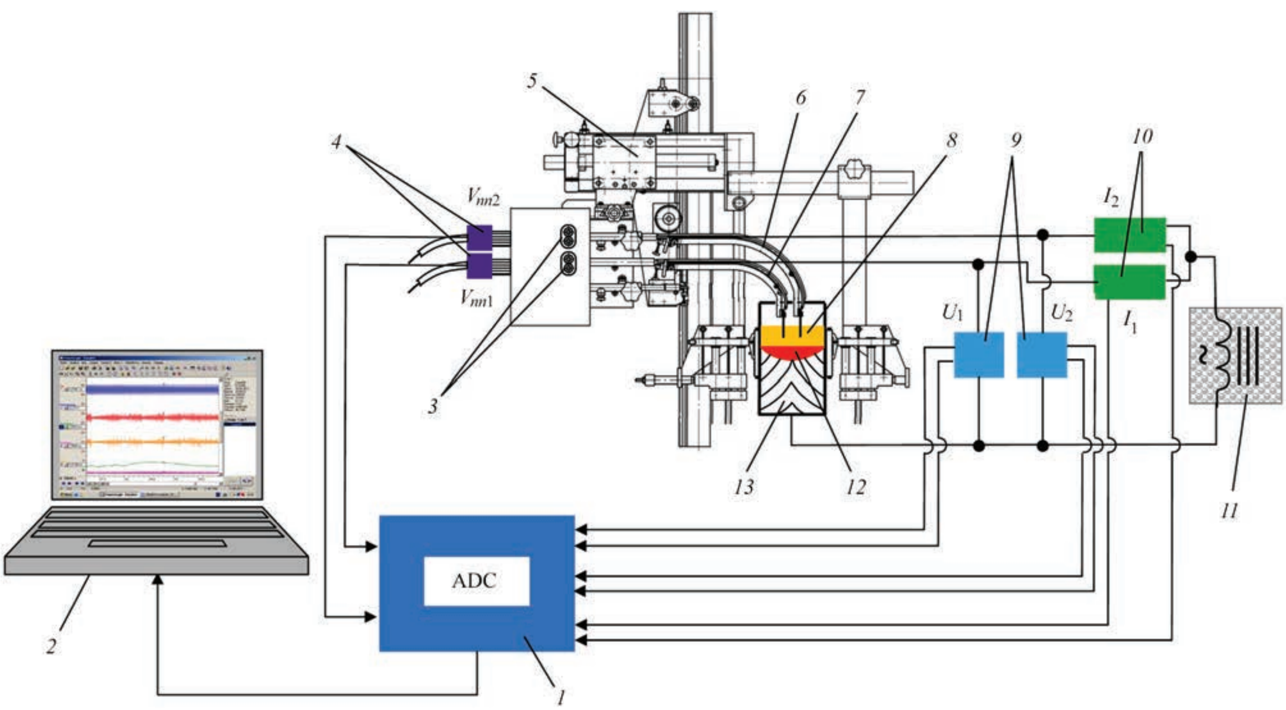

Figure 1. Scheme of high-speed recording of electric parameters of ESW mode: *1* — ADC module E-140; *2* — personal computer; *3* — feed rollers; *4* — sensors of electrode wires feed speed; *5* — welding device A-535 UKhL4; *6, 7* — upper and lower nozzles; *8* — slag pool; *9* — sensors of voltage on nozzles; *10* — welding current sensors; *11* — power source; *12* — metal pool; *13* — weld

*To specify the physical nature of the term «discharge», additional investigations will be conducted.

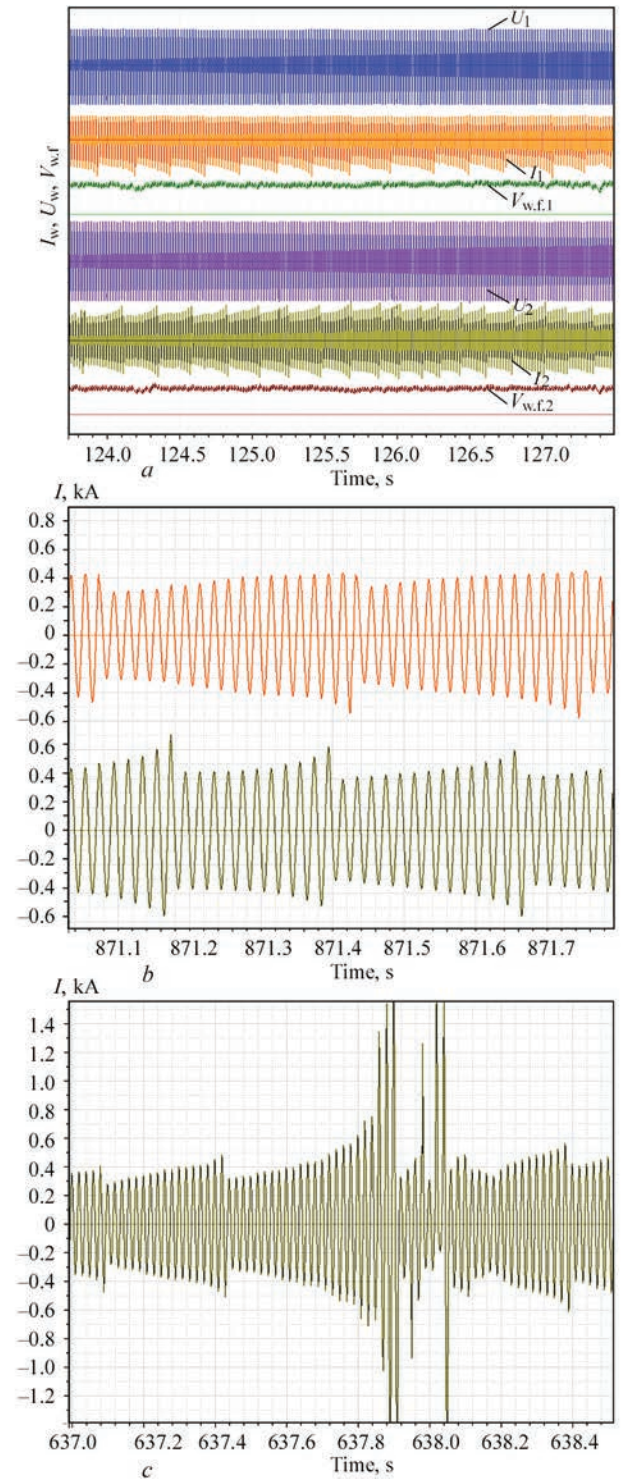

Figure 2. Fragments of recording oscillograms of parameters of the mode of ESW (I_w, U_w, $V_{w.f}$) with two electrodes: *a* — general view of the process with duration of 3.8 s; *b* — fragment of I_w recording in the interval of 871.0–871.7 s; *c* — oscillogram of I_w on the second electrode in the interval of 637.0–638.4 s

The aim of this work was to study the relationship between the phenomena visually observed in the welding zone and the basic electric parameters of the welding process mode.

The methods of performing experimental works are the following:

1. Using the device A-535UKhL4 and the AC power source TShS 3000-3, ESW of specimens of a low-alloyed steel 09G2S of 60 mm thickness was performed in the modes identical to those used in the work [8] ($n = 2$, $d_e = 3$ mm, $h_w = 45$ mm, $V_{w.f} = 112$ and 158 m/h, $B = 27$ mm, flux AN 8)*;

2. In the process of welding, a high-speed recording of electrical parameters of the mode (I_w, U_w, $V_{w.f}$) was performed using the Hall sensors, ADC module E-140 and the software «Power Graph»;

3. The numerical values of electric parameters of the welding process (I_w, U_w, $V_{w.f}$) were recorded at a frequency of 10 thou records per second (filming frequency was 100 frames per second);

4. Simultaneously with the recording of mode parameters, measurements of the slag pool temperature were performed with a digital recording of results. The thermocouple VR 5/20, installed in a protective heat-resistant case, the working end of which (immersed in a slag pool) was lined with a self-sintering graphite mass, was immersed into a slag pool to the 30 mm depth. Indications and recording of thermocouple potentials in the continuous mode were performed using the digital voltmeter VTs 7-21 and a video camera. Since the well-known temperature recording devices are very inertial, the proposed method allowed recording changes in temperature with time at the higher resolution.

The diagram of electrical connections during experiments on recording the basic electric parameters of the mode is shown in Figure 1.

The general view of the obtained oscillograms of the basic electric parameters of the welding mode with two electrode wires is shown in Figure 2. Here, a fragment of the high-speed recording of welding current, voltage on the slag pool and feed speed of the electrode wires in both nozzles are presented (Figure 2, *a*).

As a result of the analysis and comparison of visual effects of filming and recorded oscillograms of electric parameters of the mode at a qualitative level, the following regularities were established.

On the oscillograms of the set ESW mode, as well as on the frames of filming, the cyclic nature of welding process was clearly recorded, which is characteristic of each of the two wire electrodes and is determined by the dynamics of melting of each electrode. In this case, some shift in the peak values of welding current

*In the work, B.V. Tsibulenko, V.G. Yarmak, G.S. Shulzhenko and N.O. Chervyakov took part.

is observed, despite the fact that both electrodes are supplied from the same source (Figure 2, *a*, *b*).

It is shown that dimensions of energetic nucleus, values of welding current and shape of metallic pool have a common pattern of cyclic nature. In this case, throughout the whole ESW process, in the interelectrode gap, two types of cycles of different duration are observed, ending in «discharges», differing in their intensity (Figure 2). Each cycle is completed in the formation of «discharge» in the metal pool. After every 10–13 cycles with a duration of 0.3–0.4 s, ending in «discharges» of a comparatively low power in the area of the metal pool mirror, the cycles with a duration of 0.5–0.7 s are observed ending in «discharges» of high power, at which the nucleus mass reaches the bottom of the metal pool, causing a splash of superheated metal of the pool to the edges of base metal at a high rate (1.1–1.5 m/s).

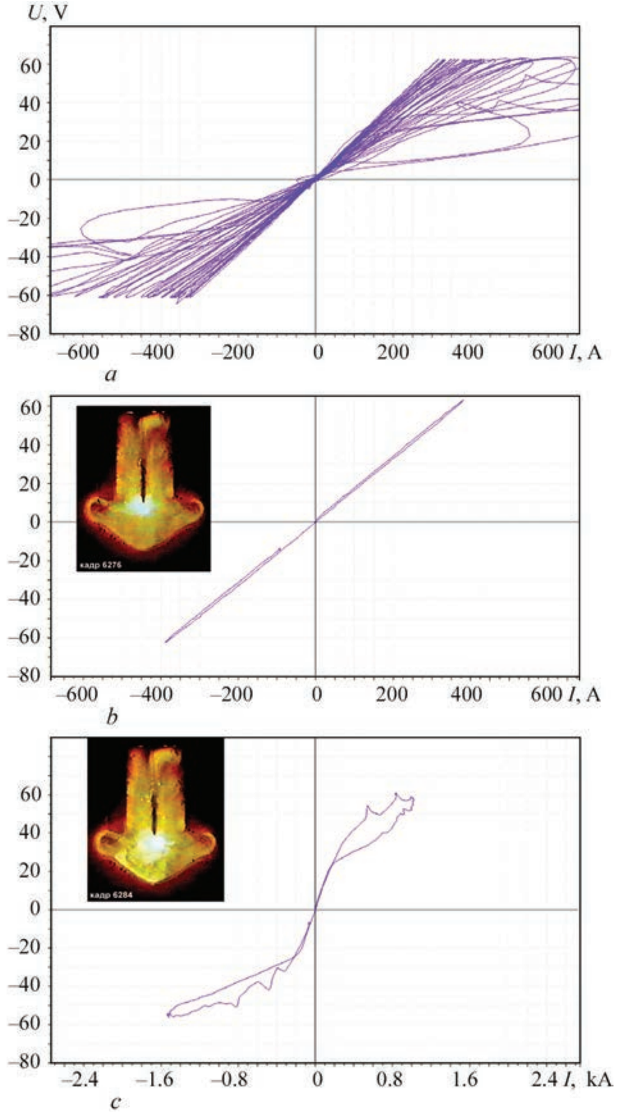

Figure 3. Voltampere characteristics of a cycle with a duration of 0.5 s on one electrode and the corresponding photos of welding zone: *a* — full cycle (see Figure 2, *c*); *b* — beginning of the cycle (0.04 s); *c* — «discharge» at the end of the cycle (0.04 s)

Thus, in the region of 3.5 s, 15–17 «discharges» of comparatively low power are noted (Figure 2, *a*). The beginning of a cycle with a duration of 0.4 s, ending in a low-power discharge (Figure 2, *b*), is characterized by a low value of welding current, equal to 312 A, and the minimum size of energetic nucleus. By the time of ending the «discharge», the welding current is gradually increased to 622 A. Simultaneously, with the increase in current, the size of the energetic nucleus increased, which shifted to the metal pool mirror. The voltage at the slag pool was changed slightly: in the range of 1.0–1.5 V.

Figure 2, *c* shows a fragment of the oscillogram, where the intensity of the current increment had a different nature. Here, a cycle with a duration of 0.5 s, ending in a «discharge» of high power, begins with a welding current value equal to 412 A, and ends in a value of 1580 A. At the same time, simultaneously with the increase in welding current, the region of energetic nucleus increases from 25 to 200 mm^2. In the

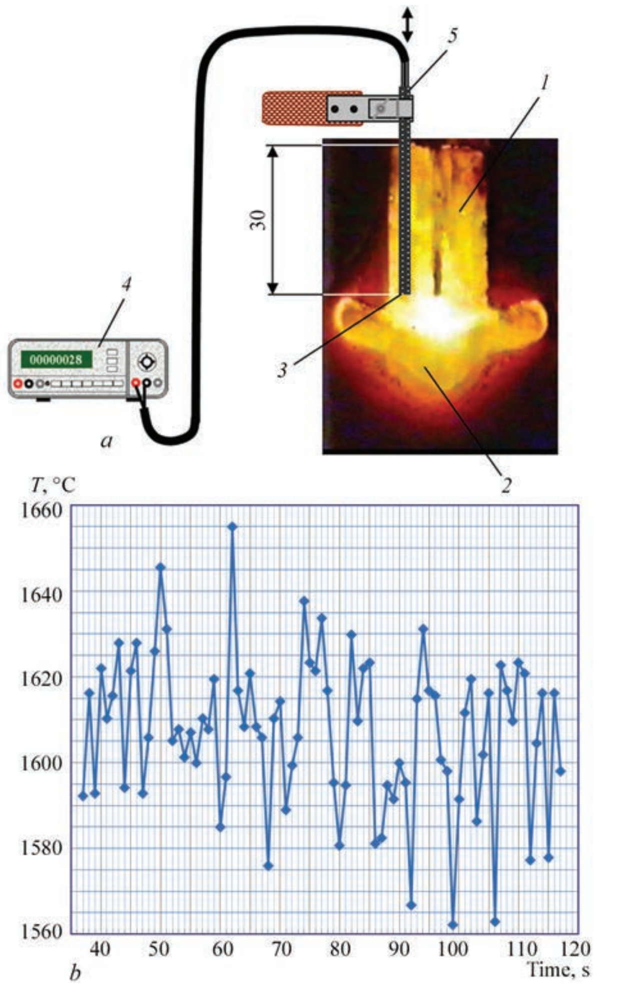

Figure 4. Scheme of measurements of temperature of the slag pool (*a*) (*1* — slag pool; *2* — metal pool; *3* — place for deepening of thermocouple; *4* — digital voltmeter; *5* — probe with thermocouple in a special protective case) and fragment of variation of its temperature (*b*)

region of sharp current peaks, the voltage at the slag pool decreases by 3.0–4.0 V.

The resolution of the used methods for measuring electric parameters of the mode allowed recording changes in welding current and voltage starting from 0.001 s. The comparison of oscillograms of the welding current with the video frames of filming in the limits of one cycle allowed studying the dynamics of «discharge» formation from the beginning to the end of its existence (Figure 3). It is shown that the end of existence of a «discharge» and the transition of its mass in the form of electrohydrodynamic impact into a metal pool is characterized by a sharp increase in welding current (Figure 2, *c*) and thermal energy in the interelectrode gap.

Comparison of the dynamics of variation in the shape of metal pool with electric parameters of the mode showed that at the end of a high power «discharge», the mass of metal pool instantly moves down and, reaching its bottom, it moves upward the welded edges by fusion of the base metal grain boundaries.

The measurements of temperature of the slag pool near the electrode melting zone showed that its change is also cyclical in nature, however, a direct correlation with cyclic changes in welding current and sizes of the nucleus was not established (Figure 4). In this case, the peaks of the maximum temperature of the slag pool are observed after the completion of 3–7 high-power «discharges». Despite the fact that insufficient resolution of the used instruments did not allow establishing the correct relationship between the results of measurements of temperature of the slag pool and frequency of the formation of «discharges», it can be assumed that the general tendency of cyclical changes in temperature is observed.

Conclusions

1. Based on the analysis of the results of direct visual investigations of the welding zone through an optically transparent medium and oscillograms of parameters of the steady state of ESW mode (I_w, U_w, $V_{w.f}$), the existence of some kind of energetic nucleus in the molten slag between electrode wire and the mirror of metal pool was confirmed, formed under the action of electric potential between the base and electrode metal in the welding zone.

2. Comparative analysis at the qualitative level of dynamics of changes in the geometrical parameters of the welding zone and the basic electric parameters of welding process showed that the sizes of energetic nucleus in the molten slag, the value of welding current, the number of discharges and the nature of shape of the change of metal pool have a common cyclical pattern. Moreover, each cycle ends in a «discharge» into the metal pool.

3. For further expansion of ideas about the processes occurring in the interelectrode gap at ESW using wire electrode and the development of methods for controlling heat input to the base metal by controlling the shape and intensity of «discharges», as well as conditions for existence of energetic nucleus, it is necessary to conduct additional experimental investigations providing a correct synchronization of the fixed video effects of welding zone with the results of recording the electric parameters of the mode.

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