MELTING OF ELECTRODE AND BASE METAL IN ELECTROSLAG WELDING

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The present article is devoted to the problems of study of physical nature of electroslag welding using development of new methods and application of existing ones for investigations of processes of fusion welding. The results of study of electroslag welding process by wire electrode were given using method of direct visual observations through the optically transparent medium of phenomena running in the welding space and further shot-by-shot processing of materials of rapid filming. The analysis was given and description of some phenomena observed in the selected basic cell of welding space: melting of slag and electrode, formation of central nugget of an interelectrode gap in the form of slag-metal-gas plasma-type discharge, evolution of heat power and its dissemination in welding space and also numerous sizes of its basic geometric parameters. The obtained detailed conceptions about the physical nature of electroslag process allow more efficient using of its advantages in the development of new technologies and equipment for manufacture of thick-sheet massive welded metal structures. 28 Ref., 1 Table, 7 Figures.

Keywords: *electroslag welding, welding space, slag pool, interelectrode gap, maximum temperature zone, active zone, interelectrode gap nugget, slag-metal-gas plasma-type discharge, melting and transfer of molten metal, weld formation, rapid filming and photography*

Since the invention and successful application of electroslag welding (ESW), being always the object of thorough attention among the scientists, more than fifty years have passed. At the initial stage the technical and economic advantages of this method predetermined often the priority of development and implementation of equipment and technological modifications of ESW.

However, the first investigations carried out at the dawn of development of ESW by the colleagues of the E.O. Paton Electric Welding Institute [1–18] and other research, industrial enterprises of the USSR [19–23], and also foreign specialists [24, 25] allowed the theoretical grounding of application of technological methods and temperature-time conditions as applied to different industrial structures. In the first turn the works on stabilization and control of welding process [6], automatic adjustment of level of metal pool [10, 12, 15] should be noted. The same important were the investigations of effect of welding conditions on quality of metal of welded joint [2], study of temperature field and thermal cycle and also heat balance of the welding process [14, 17, 19, 20, etc.].

Today ESW is challenging in the heavy machine building, especially in manufacture of welded metal structures of large thicknesses [25–28], therefore the problems of improvement of efficiency of use of heat energy in melting of filler and base metal, optimization of methods of monitoring and control of ESW and also activation of investigations of this process remain still urgent.

The theoretical and practical conceptions about the phenomena occurring in ESW (running mostly at the closed isolated space), obtained earlier, were mostly based on the application of methods of indirect observation [2, 5, 6, 11]. To have a look inside the welding space (in direct meaning) became possible due to rapid filming and photography through the heat-resistant optically transparent medium [18], which is installed instead of copper forming device, cooled by water (Figure 1). As the welding current, passing through the slag pool, makes it opaque, to see the real character of electrode melting and transfer of molten metal into the metal pool became possible only at maximum approach of wire electrode directly to the surface of a quartz glass. Thus, through the surface of transparent medium the plane image (projection of cross section) of welding space is seen, which is located in the plane of moving electrode approached to the glass, i.e. the processes of melting and transfer of electrode metal in the slag pool are observed.

One can assume that the processes like these will run also in the melting zone of the second electrode closed from observation of slag pool. The further investigations of EW process using wire electrode were carried out basing on this procedure, including:

- direct rapid filming and photography of ESW process through the optic transparent medium of specimens of low-alloyed steel of 09G2S grade 60 mm thick using two wire electrodes of 3 mm diameter at the 45 mm slag pool depth, welding gap equal to 27 mm, dry 70 mm electrode stickout, under the flux AN-8 (see Figure 1). The supply was made from AC source of TShS-3000/3 type with a rigid external characteristic. The welding process was running at the rates of wire electrode feed equal, respectively, to 3.11 and 4.39 cm/s;
- study of dynamics of change of geometric sizes of basic parameters of welding space using computer processing of frames of filming the electroslag process;
- analysis of basic electric parameters of welding process (I_w, U_w, $v_{w.f}$) and temperature mode in welding space. For this purpose, at keeping all the conditions of ESW fulfillment, recorded earlier in filming and photography, the welding of specimen with computer high-frequency record of I_w, U_w, $v_{w.f}$ and measurement of temperature of slag and metal pool was performed;
- the comparison of data on geometric parameters of welding space with the basic electric parameters of welding process and also temperature of slag and metal pool for establishment of frequency-temporary coincidences of a pulsed nature of electrode metal transfer and changes of welding current.

Below the results of visual investigation of welding space in ESW using wire electrode (first and second items) in isolated closed zone formed by edges being welded, forming devices, weld and mirror of slag pool, where melting of electrode and base metal as well as weld formation occur, are given.

For the selected welding conditions one wire electrode is intended for 30 mm thickness of metal being welded. Therefore as an optimal cell per one electrode of 3 mm diameter the welding space was selected limited by the sizes $B \times S \times h_{sl}$, where B = 27 mm — width of welding gap; S = = 30 mm — thickness of metal being welded; h_{sl} = 45 mm — depth of slag pool.

The analysis of visual observations of the welding space (Figure 2) confirms that in this most responsible link of electric circuit, representing the concentrated ohmic resistance, the main heat energy is formed and evolved which is further transferred to the electrode and base metal.

In the welding space, the longitudinal section of which in the plane of electrode axis conditionally resembles the shape of turned-over «mushroom», the single, usually visually non-visible components (see Figures 1 and 2) — slag pool, metal pool, line of solidification front, weld and wire electrode — can be distinguished.

In general, all the parameters of welding space, indicated in Figure 2, are correlated and continuously changed with time. It is clearly seen that between two solid metallic conductors (base metal and wire electrode) the electric conductor in liquid form constantly exists. In the first approach it should be noted that its central part can be defined as a nugget of the interelectrode gap. The sizes and shape of a weld are mainly determined by the amount and character of heat dissemination in welding space, here, the edges of base metal are fused higher than the level of metal pool mirror.

The slag pool, representing the melt of mixture of oxides, salts, sulfides and other components, is a conductor of electric current and is governed by the Ohm law. It is known that in the slags the ion conductivity prevails [1, 2, 10]. In the total volume of slag pool, having, as compared to the metal being welded, the considerably higher Ohm resistance in general and in the central nugget of interelectrode gap, in particular, the conversion of electric power into the heat one is occurred.

The upper boundaries of slag pool are distinctly outlined by the mirror of its almost flat surface. In the gap formed by the base metal edges being welded, such separation between slag and metallic pool is not observed (Figure 2). The slag pool in its volume is mainly, as was expected, rather non-uniform in its temperature, which is proved by its color gamma (see Figure 2). The typical regions can be distinguished in it:

- the region of the highest temperatures (area F_1), which directly contacts the edge of electrode, where the overheat of drops of molten electrode metal and slag is occurred;
- more branchy region (area F_2), which is characterized by lower temperature than area F_1, but higher than the temperature of basic volume of slag pool. Let us define this region as the active region, where heating and melting of electrode occur.

Both these zones in welding space occupy the volumes which are definite and, obviously, optimal, from the point of view of heat energy evo-

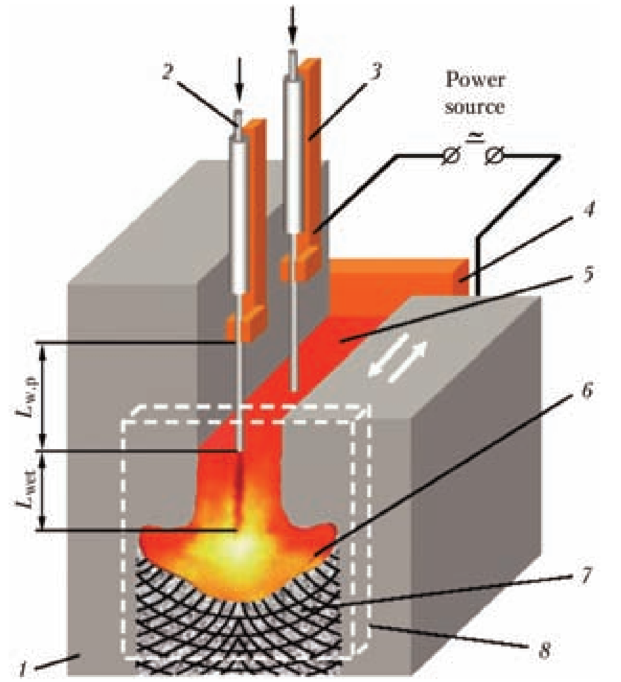

Figure 1. Scheme of specimen for rapid filming and photography of ESW through optically transparent medium: *1* — edges being welded; *2* — wire electrode; *3* — nozzle; *4* — forming device (shoe); *5* — slag pool; *6* — metal pool; *7* — weld; *8* — quartz glass (instead of reverse shoe); L_{wet} — electrode wet stickout; $L_{w.p}$ — length of wetted electrode part

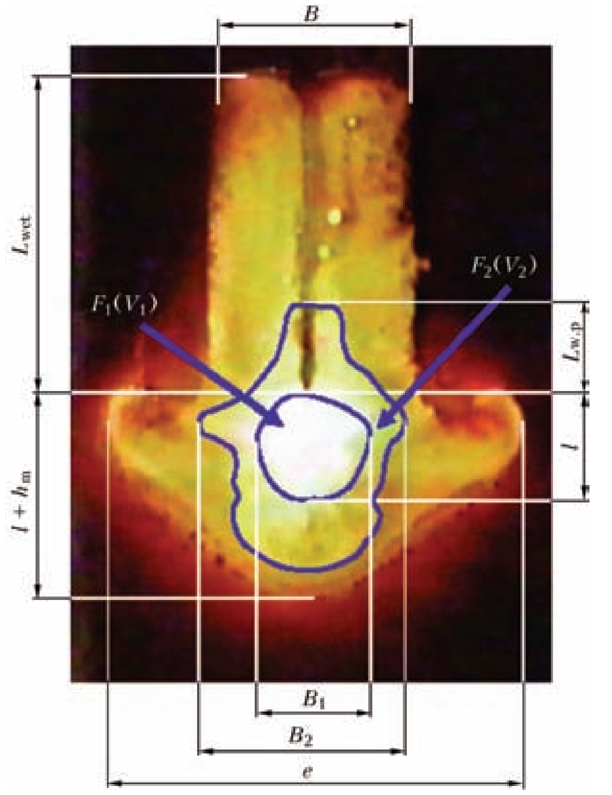

Figure 2. Scheme of distinguish of zones of space of formation of welded joint of ESW using wire electrode fixed at rapid filming through optically transparent medium and their designation: B — width of gap between the edges being welded; e — weld width; l — distance between the electrode end and metal pool mirror; h_m — metal pool depth; $F_1(V_1)$ — zone of the highest temperatures; $F_2(V_2)$ — active zone; B_1 — width of zone of the highest temperatures; B_2 — width of active zone

lution and stability of welding process. The observed zones F_1 and F_2 should be considered and represented as longitudinal sections of the corresponding volumes V_1 and V_2 close to the bodies of rotation of mentioned plane sections around the axis of electrode.

The volume of zone of the highest temperatures V_1 is actually a central nugget of the interelectrode gap. It is obvious that its composition, shape and state are the most important characteristics of the electroslag process. At the selected parameters of welding mode the nugget (see Figure 2) exists during the whole period of welding changing in volume in a pulsed form according to the definite laws. The visual observations of the process give grounds to assume that according to its composition and state the volume of a nugget V_1 represents some slag-metal-gas discharge of plasma type, which is formed in slag pool as a result of current passing through it. It is formed and exists in a pulsed mode. It is clearly seen that this discharge has a considerably higher temperature than the rest regions of slag pool, and as a conductor of electric current is subjected to the influence of electromagnetic fields generating in the welding circuit. The physical state of this zone (e.g. temperature, conductivity, etc.) should be determined using special physical methods of investigation, which are applied in study of discharges of the kind.

In Figure 2 one can see how alternating welding current (for example, in the first semi-period) is transferred from the electrode to a slag pool. The contacting metallic hard surface of electrode can considerably change in this case: from the size equal to cross section of edge of electrode (7.1 mm^2), to the value of general area of side surface of wet electrode stickout (about 100 mm^2) which contacts (wetted) and fused by a slag. Therefore, on the contact boundaries of volumes V_1 and V_2 the density of current and conductivity are changed continuously. Welding current is spreading in the volumes of these zones passing through the contact surface with mirror of metal pool and partially through the fused edges being welded, arranged over the metal pool. From the metal pool through the surface of solidification front and fused edges of base metal the electric circuit is closed to the base metal and then further to power source. Here, the area of contact surface of base metal is equal to the area, which is wetted by the molten metal and slag. It many times exceeds the contact surface of wire electrode. Therefore during change

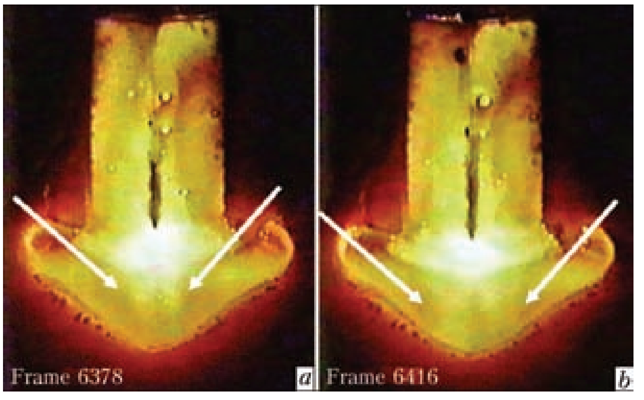

Figure 3. Constantly existing current-conducting channel (boundaries of channel are marked with arrows) from zone F_1 to metal pool, the sizes of which are determined by its maximal width B_1 (see Figure 2)

of polarity (second semi-period) the conditions of welding current passing are changed. This phenomenon is visually observed by alternation of change of brightness of glowing of adjacent frames. Here, around the perimeter of zone of the highest temperatures V_1, coaxially to the electrode, the bright current-conducting channel, contacting the metal pool, is constantly observed (Figure 3).

During passing of welding current the basic part of heat energy is mostly evolved on the contact boundaries (see Figure 2): surface of electrode–region of volume V_1; surface of electrode–region of volume V_2; region of volume V_1–metal pool; region of volume V_2–metal pool; metal pool–base metal (edges + weld); slag pool–edges of base metal.

It is obvious that at the constant existence of several contact zones between liquid conductors with different properties (for example, conductivity, temperature, viscosity) in the interelectrode gap, some concentration of heat energy, evolved in the central nugget of interelectrode gap, is occurred.

Moreover, the vector of movement of heat energy of region of volume V_1 is mostly directed towards the metal pool, as its heat conductivity

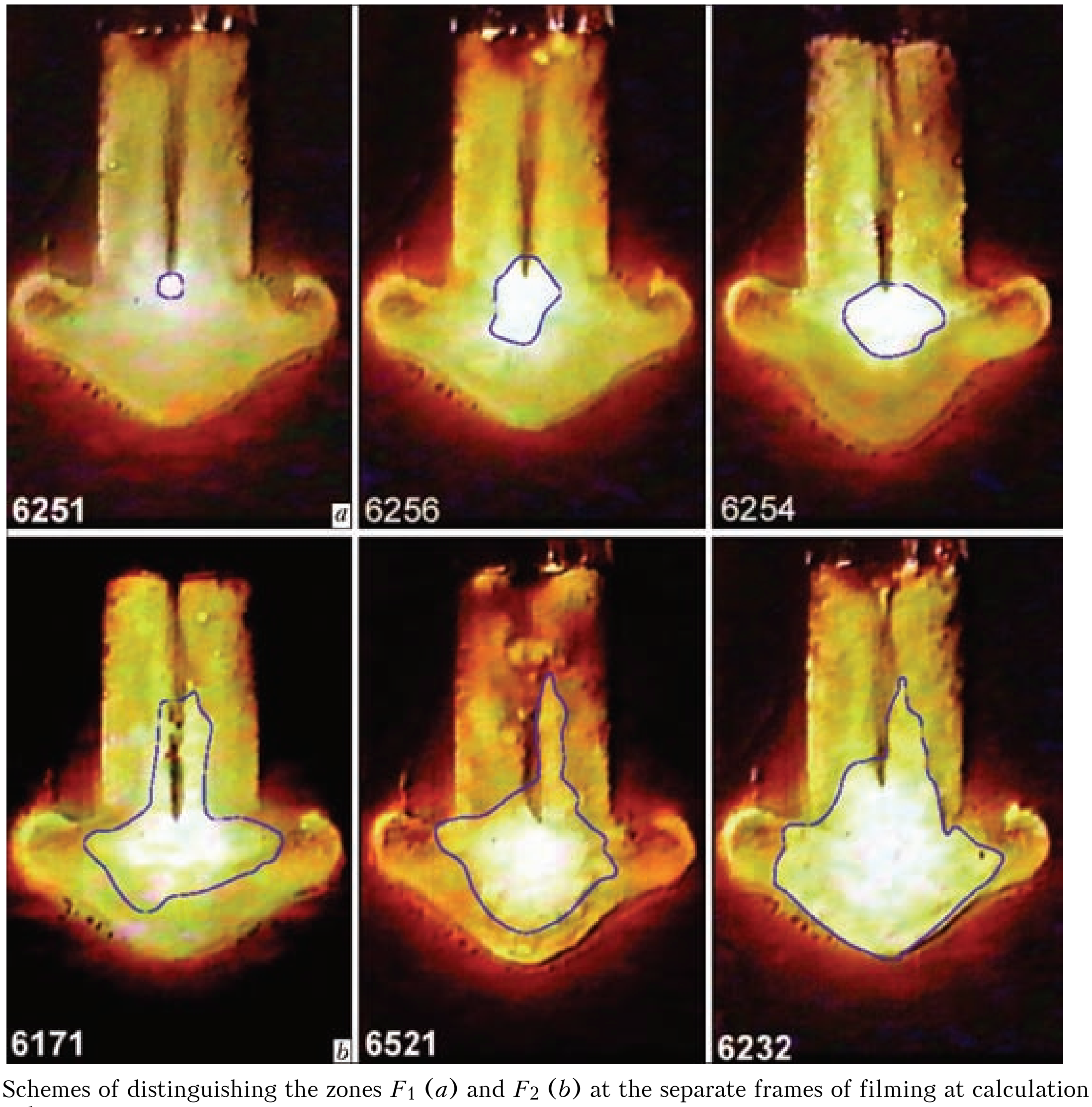

Figure 4. Schemes of distinguishing the zones F_1 (a) and F_2 (b) at the separate frames of filming at calculation of their areas and volumes

is higher than that of a slag. The slag pool and edges being welded receive the main heat pulse from metal pool as the most moving medium, formed in welding space. The heat energy transferred to slag pool is consumed for preheating and partial fusion of edges being welded, wet electrode stickout and also heating of slag pool. In addition, a part of volume of slag pool, located higher than active zone V_2, is not a conductor of welding current, i.e. it does not mainly evolve, but consumes heat energy and provides equilibrium state of F_1 zone and also protection of metal pool from the atmosphere effect.

In determination of fraction of areas (volumes) of zones F_1 and F_2 in total balance of selected cell one can divide them conditionally for convenience into more simple plane geometric figures (Figure 4) and calculate their areas. As it was mentioned earlier, they are actually the cross sections of bodies (volumes) of rotation relatively to the axis of electrode, their areas can be converted into the proper volumes. Examples of changes of these areas with time, as well as correlation of volume V_1 to the total volume of selected cell of welding space V, are described in Figure 5.

For the selected time interval, for example, of 0.45 s, the area of zone F_1 (Figure 5, *a*) can change within wide ranges (from 25 to 200 mm^2), the area of F_2 zone changed at the same time interval within the ranges of 350–550 mm^2 (Figure 5, *b*). The fraction of volume of nugget of interelectrode gap V_1 to the total volume of selected cell of welding space V is changed negligibly (Figure 5, *c*, *d*). These data prove that main heat energy, evolved in ESW, is really concentrated in the volume of zone of the highest temperatures V_1.

The metal pool is formed of molten electrode metal, which is supplied into it mostly in portions from the volume V_1 (zone F_1) and base metal fused along the edges. It is established that at stable proceeding of the electroslag process the alternation of relatively calm character of formation and movement of mass of volume V_1 into metal pool, and its explosive-like transfer is observed. The explosive type character of transfer of electrode metal is a consequence of some pulsed accumulation of heat energy in the overheated nugget with the subsequent explosive type discharge of the inerelectrode gap. As a result, at the selected modes of ESW the local advance accumulation of evolved heat energy and comparatively its delayed consumption (heat removal) by the edges of base metal is observed. This phenomenon influences greatly the shape of interelectorde gap and character of drop transfer.

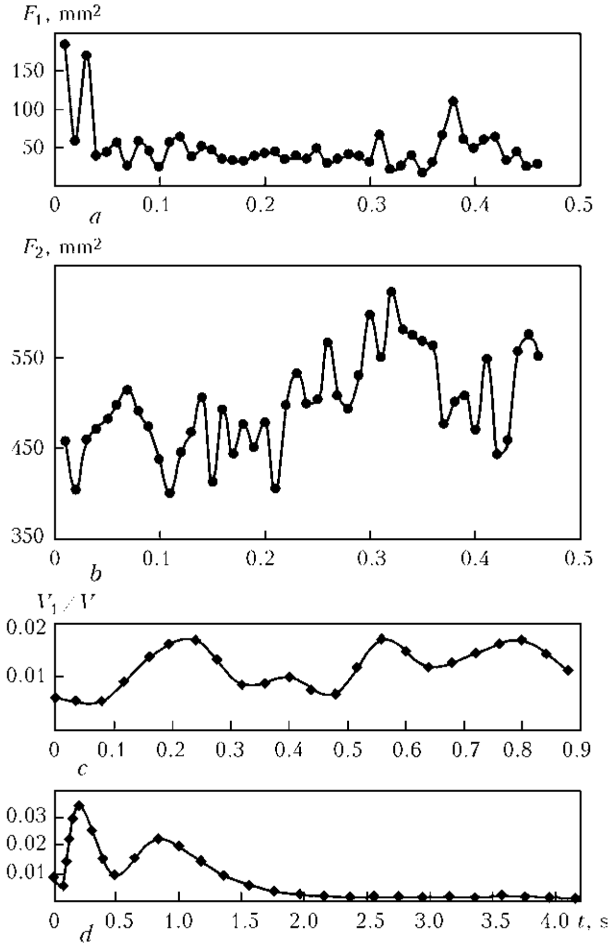

Figure 5. Changes of areas F_1 (*a*), F_2 (*b*) and fraction of volume of zones of the highest temperatures V_1 in total volume of welding zone at $v_{w.f}$ = 3.11 (*c*) and 4.39 (*d*) cm/s

The accumulated heat leads to increase of rate of electrode melting, causing pulsed growth of conductivity and mass of volume V_1 and also the welding current. When under the influence of heat and electric factors the powerful explosive discharge of V_1 volume occurs, the value of wet stickout decreases (parameter l (see Figure 2) increases) and, as a consequence, the value of welding current is decreased. After that the general cycle is repeated and origination, formation and growth of a new volume V_1 begins. The frequency of formation and volume of slag-metal-gas discharge of plasma type depends on selected parameters of welding conditions. Thus, at the rate of electrode feed of 4.39 cm/s during the preset welding period of duration of one discharge equal to 0.15 s, 0.24 g of electrode mass was melted, and speed of dissipation of heat energy (wave) in metal pool, i.e. the movement of heat flow of volume V_1 mass, amounted to about 1.5 m/s.

If the metal pool has a clear, slowly changed interface with weld (along the line of solidification front), then such stable interface between

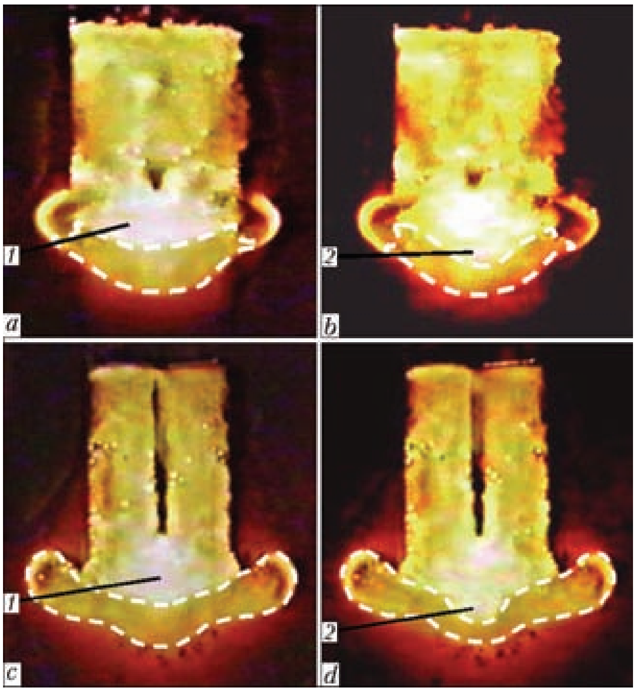

Figure 6. Dynamics of change of metal pool shape at $v_{w.f}$ = = 3.11 cm/s at the beginning (*a*, *b*) and steady process (*c*, *d*): *1* — zone F_1 formation; *2* — explosive-like penetration of mass of volume V_1 into the metal pool

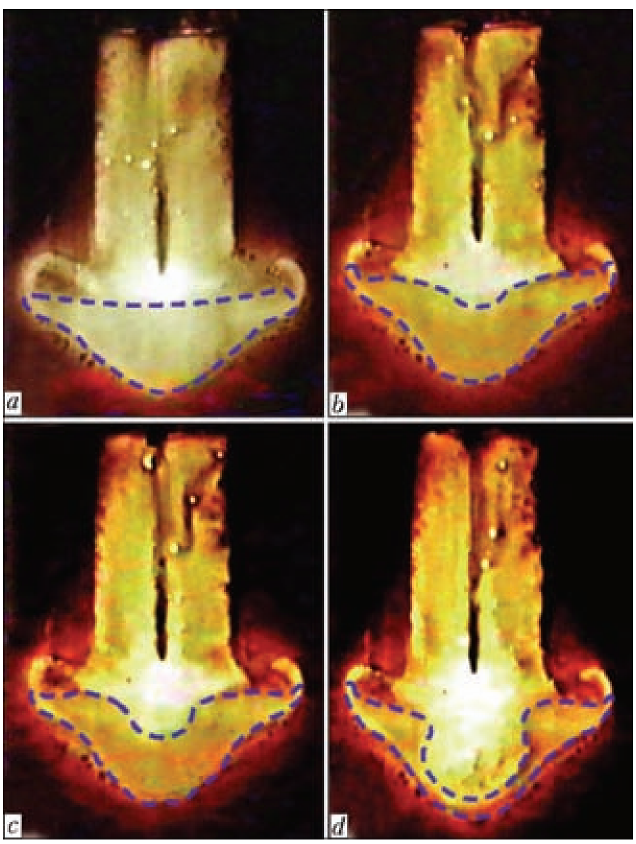

Figure 7. Change of shape of metal pool at $v_{w.f}$ = 4.39 cm/s at the moment (dotted lines mark the boundaries of metal pool) of origination of volume V_1 (*a*), beginning of «forcing» of mass of volume V_1 into the metal pool (*b*), growth of volume V_1 mass (*c*), and explosion of mass of volume V_1 with forcing out of metal pool (*d*)

the slag pool and mirror of metal pool in the process of melting is too difficult to determine. During the whole electroslag process the mirror of metal pool (especially under electrode) has a complicated concave conical surface which changes constantly (Figures 6 and 7). Under the influence of mass of volume V_1 and occurring hydro- and electrodynamic forces, the shape of surface of metal pool mirror changes constantly. At the moments, when the mass of volume V_1 reaches bottom of metal pool (surface of front of weld solidification) by the pulsed energy of powerful directed discharge, one can observe the «splashing» of metal pool into the slag beyond the limits of equilibrium state (Figure 7, *d*). As a consequence, the overheated slag-metal-gas mixture together with metal pool moves upwards along the planes formed by the front of solidification and forming devices. Then, then the molten metal is flowing down already under the effect of gravity forces. The intensive transfer of heat energy to the slag pool and edges being welded occurs by alternating pulses. The heat pulse from metal pool is directed to the earlier fused edges of base metal under the angle of about 90°, therefore it transfers them maximum energy. The upper part of edges in the gap, contacting the slag pool and being above the level of end of electrode, is heated less intensively and, as a rule, does not fused by a slag. As even skull crust can exist at the boundary, then mainly due to this the mushroom shape of edges penetration is observed.

The line of solidification front practically repeats the shape of mirror of metal pool. The concept of depth of metal pool, usually determined from the macrosections, does not meet its real parameters during running of electroslag process (see Figures 6 and 7). It should be noted that periodic «splashing» of portions of metal pool causes partial repeated fusion of crystallized weld metal along the solidification front.

The intensive rotation of mass of volume V_1 around the axis coaxial to the electrode is also observed. As a result the heat flows can deviate aside from the axis of electrode. However the main fraction of heat energy is concentrated along the axis of electrode movement, therefore the surface of crystallization front is maximum concave along the weld center in particular.

The melting of electrode metal occurs mainly in the region of active zone F_2. Moreover, the electrode is fused along its side surface, wetted by the slag (contacting the active zone). The fused cone-shaped surface of end of metal electrode is the main contact element of electric circuit, through which the welding current is directed to slag pool from the electrode.

The drop formed from the molten metal, which is flowing along the side surface of electrode, is directly in the zone of highest temperatures F_1, where its additional overheating occurs. During formation of drop it is affected by the gravity force and electrodynamic forces («pinch-effect», accelerating the moment of detachment and movement of drop from electrode).

It was established that the shape of end of the electrode during the welding process is mainly cone-shaped (the electrode is sharpened downwards). However at the moment of powerful pulse explosion of discharge sometimes lump-like rupture of end of conic part of electrode is observed, as a result of which the wet stickout is noticeably decreased, and the distance l is increased. It is rationally to add that in the so-called wet stickout L_{wet}, which defines the depth of submersion of electrode into the slag pool, the part should be specially distinguished wetted by the slag $L_{w.p}$ (see Figure 2), influencing the welding current and character of electrode melting.

For the investigated conditions the alternation of three-four and more small discharges with one-two big explosions was noted. The shape of edges fusion is explained by the character of heat transfer from the metal pool to the base metal and partially by the conditions of existing of metal pool under the effect of gravity force and forces of surface tension. The contour of edges penetration represents the isothermal surface corresponding to the melting temperature of base metal. In the zone of electrode metal melting the intensive gases evolution is observed, which are evolved practically through the whole volume to the mirror of slag pool (see Figure 3). The evolution of gases is observed also in the region of maximal penetration of edges of base metal (see Figure 3, frame 6378), which can be explained by getting of gases to the metal pool with the mass of volume V_1 (at the moment of explosion). The evolution of gases at the electrode was not visually noted.

In study of welding zone the different computer programs of precise discrete measuring were used, by means of which the values of geometric parameters were determined (see Figure 2). The sizes were determined during processing of fragments of filming frames, performed at the frequency of 100 frames per second for two modes of ESW — at $v_{w.f}$ = 3.11 and 4.39 cm/s, respectively. The determination of real linear sizes of geometric parameters was performed as applied to known set value of real welding gap between the edges B = 27 mm. The error of measurements amounted to 0.5–2.5 %. For clearness some results of measurements (the limits of parameters values) are given in the Table.

Real limits of change of numerical dimensions of main geometric parameters for the selected cell of welding space depending on wire electrode feed rate

Parameter (see Figure 2) and dimensions	$v_{w.f}$, cm/s	
	3.11	4.39
h_m, mm	4–10	4–16
$l + h_m$, mm	20–22.5	20–26.8
L, mm	30.5–33.5	30.5–40.5
e, mm	48–51.5	54–60
F_1, mm^2	100–210	20–200
F_2, mm^2	190–550	–
B_1, mm	10–22	5–25
B_2, mm	22–28	25–26

It is known that the main criterion for evaluation of quality of a weld is the coefficient of weld shape $\psi = e/h_m$. Though the depth of metal pool in the process of welding is changed continuously, the width of weld e is changed negligibly. The section area of metal pool can amount to 30 % of area of plane of section of welding space (along the axis of electrode) and its mass for the mentioned cell is in the limits of 115–125 g. It is the main factor of influence on the weld shape. For investigated modes of welding the average value is ψ = 5.7–7.0.

Conclusions

1. At the stable process of ESW the wire electrode is fused in a slag pool along the surface wetted by a slag. During getting of molten electrode metal into the gap between the electrode and mirror of metal pool, the slag-metal-gas plasma-type discharge is formed, which is transferred to metal pool by alternating pulses of overheated mass by electro- and hydrodynamic impacts. Reflecting from the bottom, the overheated mixture, including metal pool, is lifted to the edges being welded and transfers heat energy to them and also to a slag pool.

The explosion character of transfer and intensive mobility of overheated slag-metal-gas mixture provide a mushroom shape of penetration of edges being welded.

2. The presence of cyclic repeated slag-metal-gas discharges of plasma type, observed during investigations, is the character feature of electroslag process using wire electrode at all the stages of its existence.

3. Slag pool in ESW is rather non-uniform in temperature, which is evidenced by its fixed color gamma, where characteristic regions can be distinguished:

• slag-metal-gas discharge of plasma type (volume V_1), which contacts directly the electrode and has the highest temperature;

• active zone (volume V_2), which as compared to V_1 is characterized by lower temperature, but being higher than the temperature of main volume of slag pool;

• in these regions the electric energy is transformed into a heat one, the melting and transfer of electrode metal, as well as weld formation, are occurred;

• part of volume of slag pool, located over the zone V_2, provides equilibrium state of region V_1, protection of metal pool from the effect of atmosphere and is not a conductor of welding current in general.

4. The considered regions of the welding zone are the most important elements of electroslag process and together with electric parameters of welding conditions are used in monitoring and control of welding process.

5. Peculiarities of running of ESW using wire electrode can be taken into account during investigation of such welding methods as welding with consumable nozzle, with large-section electrode, and also electroslag remetling.

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