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CONTROL OF FORMATION OF WELDED JOINTS IN ESW (Review)

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Some technological approaches and methods for affecting the process of electroslag welding (ESW), aimed at optimisation of structure of the weld and HAZ metals, are considered. It is shown that the external magnetic fields providing the force effect on the weld pool by a contactless method are an efficient tool to control solidification of metal in ESW. The most effective schemes of electromagnetic control of the ESW process, ensuring homogenisation and refining of structure of the weld metal, are studied.

Keywords: *electroslag welding, solidification, macrostructure, weld, electromagnetic effect, hydrodynamics, magnetic field*

Electroslag welding is an efficient method for joining thick-walled pieces of alloys based on iron, titanium, aluminium, copper and other metals. One of the key advantages of ESW is its high productivity and the possibility of joining metal with thickness from 30 mm to several metres in one pass without groove preparation [1–5].

However, despite the apparent advantages, ESW is often limited in practical application because of the unfavourable effect of the thermal welding cycle and hydrodynamic processes occurring in the weld pool on formation of structure of the weld and HAZ metals. These peculiarities of ESW may lead to formation of a coarse large-grained structure of the weld metal and embrittlement of HAZ, as well as negatively affect properties of the welded joints.

As a rule, heat treatment of the welded joints eliminates heterogeneity of structure and mechanical properties of different regions of a welded joint. However, it makes the ESW process much more complicated and expensive. Moreover, it is often inapplicable for super-large parts. Different approaches are employed to decrease overheating of metal during the welding process. In a number of cases such approaches make it possible to provide the required properties of the welded joints without postweld heat treatment. However, decrease in the extent of overheating of the weld and HAZ metals was and is one of the key problems of the ESW technology [6].

In this connection, the topical problem of ESW is development of the technological approaches and methods for affecting the welding process, which are aimed at improving structural homogeneity of the weld metal and reducing the negative effect of the thermal welding cycle on the HAZ metal (Figure 1). Such methods are based on adding different modifiers and fillers to the weld pool [3, 7], utilisation of an extra dead wire [8], application of forced cooling of the weld and HAZ metals [9], portioned energy input into the welding zone [10], increase of the electrode extension [11], concurrent heating of the weld and HAZ metals for local continuous normalising [3], introduction of ultrasonic and mechanical oscillations [12], affecting by external magnetic fields [13, 14] and other principles.

Metallurgical methods for increasing the efficiency of ESW are aimed at development of new welding consumables with special strength and thermal-physical properties, which are insensitive to the thermal welding cycle. Also, different modifiers and fillers can be added to the weld pool. Such methods are efficient enough to control properties of the weld metal. However, they exert only a slight effect on the HAZ metal.

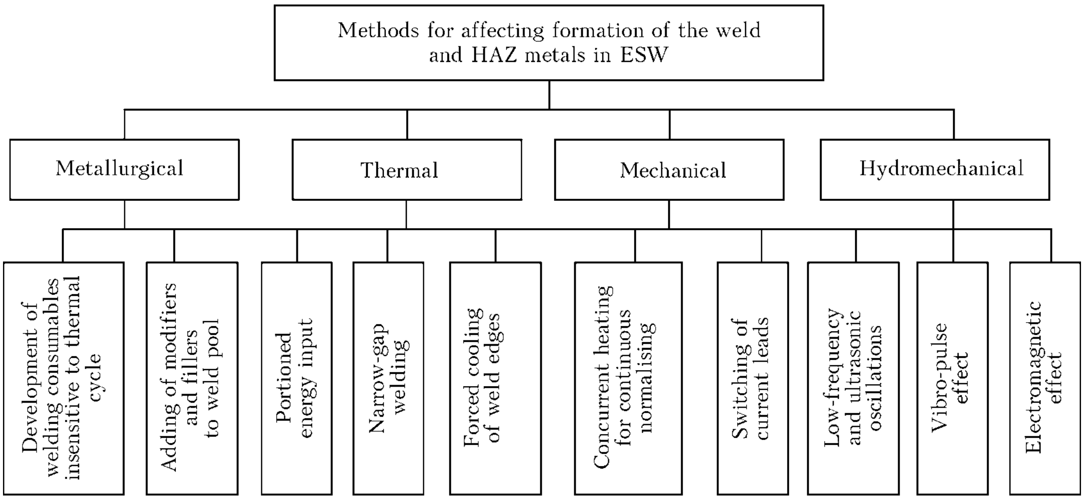

Figure 1. Schematic of technological approaches and methods used to affect formation of the weld and HAZ metals in ESW

Moreover, a change in chemical composition of the weld metal with respect to the base metal is often inadmissible.

Narrow-gap welding is one of the methods for reducing the welding heat input and narrowing the HAZ [15]. This welding method is characterised by decreased volumes of the weld pool and filler metal, and an increased welding speed. The narrow-gap welding process is similar to the standard ESW process. However, it requires the use of additional measures for prevention of short circuiting of electrodes to the weld edges and guaranteed penetration of the base metal.

Study [15] gives investigations results on development of the improved narrow-gap ESW technology to address the machine building problems. The new technology is characterised by reduction of the welding gap to 19±1 mm and utilisation of the specially developed consumable nozzle with electrical insulators, nickel-molybdenum electrode wire and neutral flux. Parameters of the suggested process and traditional ESW for 50 mm thick steel plates are given in Table 1.

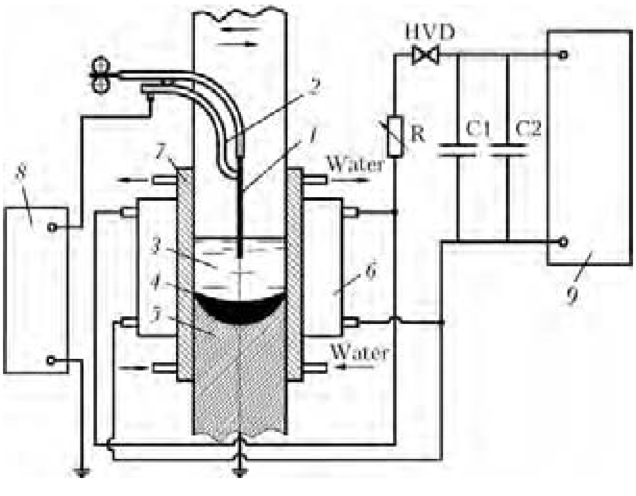

Figure 2. Scheme of ESW with concurrent electric-discharge treatment [12]: *1* — electrode; *2* — current lead; *3* — slag pool; *4* — metal pool; *5* — weld; *6* — inductor; *7* — forming straps; *8* — power supply; *9* — pulse current generator; HVD — high-voltage discharger; C1 and C2 — high-voltage capacitor batteries; R — ballast rheostat

It is noted that the new process is characterised by a high productivity and provides improved fatigue properties and impact toughness of the weld and HAZ metals. The said effects are achieved due to decreasing the heat input, optimising the shape of the weld pool and using the welding wire that improves metal microstructure. As a result, the high quality of the joints is achieved without extra heat treatment.

Based on the comprehensive investigations of properties of the narrow-gap welded joints, the US Department of Transportation issued a memorandum of cancellation of the moratorium on application of ESW in bridge construction [16].

The method of the vibro-pulse effect on the weld pool [12] was proposed for controlling solidification of the weld metal. The point of this method is as follows (Figure 2): the electric current pulses are formed by using the pulse current generator and the capacitor battery, these pulses being fed through the high-voltage discharger to the one-coil inductors located on the copper forming shoes on opposite sides of the workpieces welded. In electrodynamic interaction between the inductor and shoes the working walls of the

Table 1. Parameters of ESW of 50 mm thick plates [15]

Welding method	Welding gap, mm	Current, A	Voltage, V	Welding speed, mm/min	Heat input, kJ/mm
ESW:					
conventional	32±2	600±100	39±1	28	50
narrow-gap	19±1	1000±100	35±0.5	55	37

latter transfer strong mechanical shocks to the molten metal, which induce periodic hydrodynamic waves in it. Intensive oscillations of the liquid phase with respect to the solid one decrease the temperature gradient at the interface between the phases, inhibit growth of crystals, and disturb periodicity and orientation of dendritic solidification.

The authors give the following explanation to the mechanism of the vibro-pulse effect on the HAZ metal. Like any liquid, the molten metal is hard to compress. Hence, with propagation of a shock wave it hits edges of the base metal, thus causing refining of structure of the HAZ metal. The fusion line loses its clearly defined shape and becomes broad.

It is apparent that in this case, in addition to the mechanical effect on the weld pool imparted by the shoes, there is also the effect exerted by the electromagnetic forces generated as a result of interaction of pulses of the magnetic field with the welding current.

The possibility of refining the weld metal structure and improving resistance of the welded joints to brittle fracture and corrosion was shown by an example of ESW of steels of the VSt3sp (killed), 09G2 and 12Kh18N10T grades with the vibro-pulse effect.

Study [17] suggests the method for high-speed ESW of thick-plate steels of the 22K, 16GNMA, 16GS and other types without subsequent normalising of the welded joints. The point of the method is a forced preset-frequency change of the location where the electric current is supplied to electrodes and weld edges (Figure 3). Switching of current leads during the welding process causes redistribution of flow lines of the current in the weld pool. Besides, this leads to a dramatic change in the character of motion of the slag-metal melt and, hence, the balance of temperatures in the pool. The larger part of the energy goes to melting of electrodes, and the smaller part is transferred to the base metal. All this increases the rate of melting of the electrodes from 3 to 4 times and minimises the extent of removal of heat to walls of the base metal. It is noted that the specific energy input of the process is 25–50 kJ/cm^2, which is 4–5 times lower than in conventional ESW (104–208 kJ/cm^2). In addition, the thermal cycle of welding becomes close to that of the submerged-arc welding process.

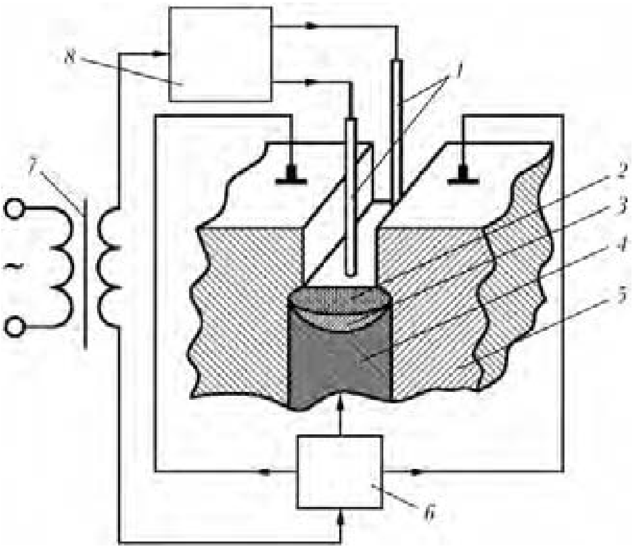

Figure 3. Scheme of high-speed ESW [17]: *1* — electrodes; *2* — slag pool; *3* — metal pool; *4* — weld; *5* — workpiece; *6* — three-channel current transducer; *7* — power supply; *8* — two-channel current switch

Investigations of the welded joints on thick-plate steels of the 22K, 16GNMA, 16GS and other types, made by using the developed high-speed ESW process, showed improvement of macrostructure and mechanical properties of the weld and HAZ metals, which excludes the use of post-

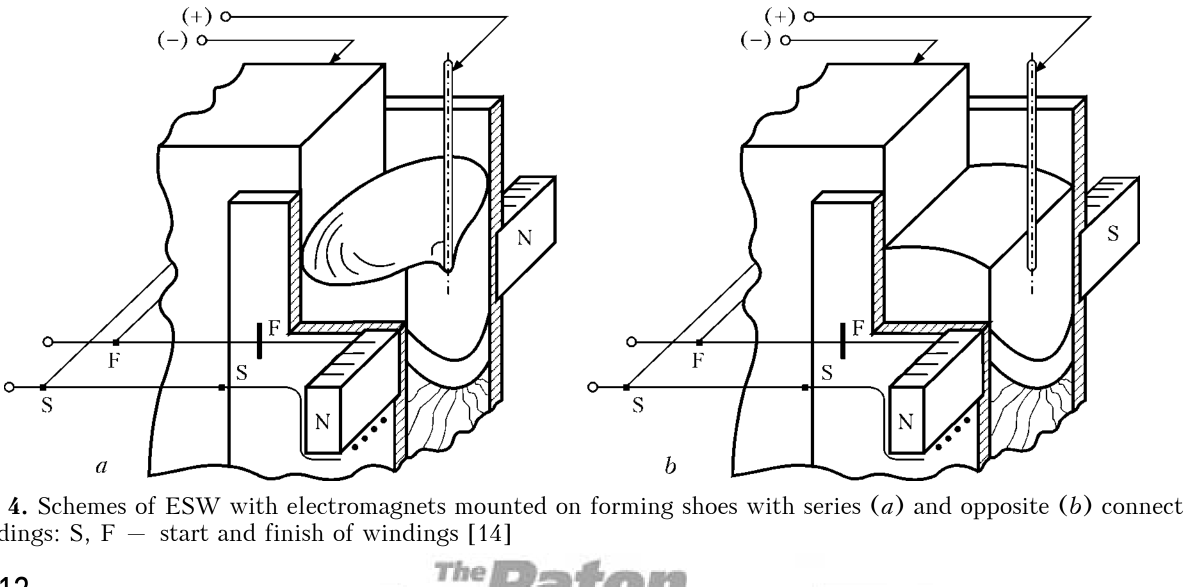

Figure 4. Schemes of ESW with electromagnets mounted on forming shoes with series (*a*) and opposite (*b*) connection of windings: S, F — start and finish of windings [14]

Table 2. Recommended parameters for ESW of steel 12Kh18N10T [14]

Welding wire	Metal thickness, mm	Parameters of welding and control magnetic field			
		I_w, A	U_w, V	B, mT	t_r, s
Sv-06Kh19N9T	23–35	550–600	Not more than 55	18–20	0.32
Sv-06Kh19N10M3T	23–35			18–20	0.32
Sv-06Kh19N10M3T	23–35			25–35	0.08
Sv-06Kh19N9T	35–45			25–35	0.32
Sv-05Kh19N10F3S2	45–60			35–45	0.32

weld high-temperature heat treatment of the welded joints.

Study [14] describes investigations of the methods of affecting the electroslag process by using the external (reversing) magnetic fields. It is noted that electromagnetic stirring of the molten pool for the ESW conditions can be provided by using the magnetic fields induced by a solenoid located on a rod electrode, by electromagnets located on the shoes, or by a welding cable passed through the gap.

It is shown that the most rational scheme of the electromagnetic effect in ESW is the use of electromagnets with a single-bar core mounted on the forming shoes (Figure 4). In this case the magnetic field penetrates the entire melt of the weld pool and affects a change in the thermal state of metal and slag.

Investigations were carried out by using carbon and austenitic steels with thickness δ = 20–60 mm in the reversing magnetic field with induction B = 5–45 mT and reversing interval t_r = = 0.08–0.32 s.

The welding parameters, including magnetic induction and reversing time, providing the electroslag process with no violation of its stability were developed. It was found that the reversing magnetic field tolerates a higher limiting value of induction compared to the unidirectional field.

It is noted that violation of stability of the process is promoted by formation of a paraboloid of revolution under the effect of the unidirectional magnetic field. The matter is that the metal pool becomes exposed near the apex of this paraboloid, which leads to the arc discharges induced between the electrode tip and surface of the metal pool.

The recommended parameters of the magnetic field and welding process for steel 12Kh18N10T are given in Table 2.

Metallographic analysis of the welded joints showed that structure of the welds made under conventional welding conditions differs substantially from that of the welds made by using the magnetic field. Their common property is a smaller transverse size of crystalline grains. Structural analysis of the welds on steel 09G2S showed both a change in shape of the inclination angle of crystalline grains and decrease in their cross section.

The main criterion for evaluation of properties of the weld metal was impact toughness, which was determined for different temperatures depending on the steel grade. Analysis of the obtained data allowed distinguishing the range of parameters of the control magnetic field in which the impact toughness of the weld metal can be increased 2–3 times, and its values can reach the

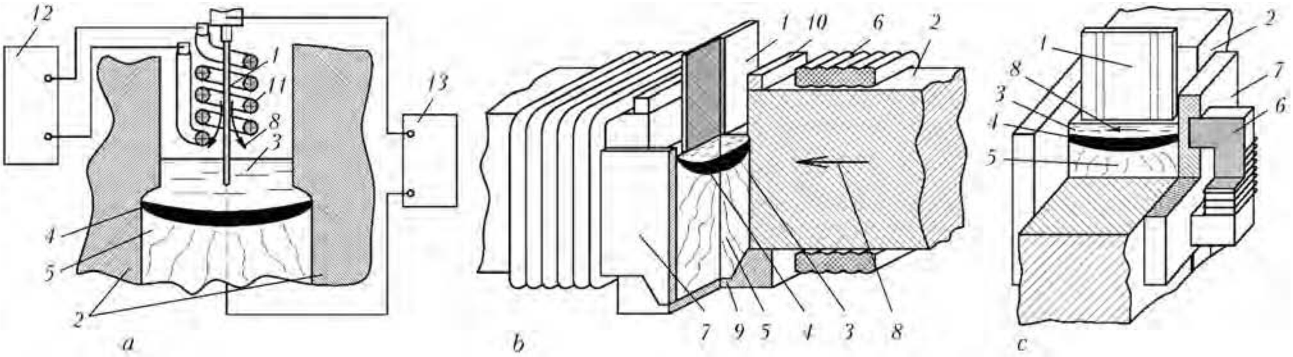

Figure 5. Scheme of ESW in longitudinal (*a*) and transverse (*b*, *c*) magnetic fields: *1* — consumable nozzle-electrode; *2* — workpieces welded; *3* — slag pool; *4* — metal pool; *5* — weld; *6* — electromagnetic device; *7* — forming straps; *8* — magnetic field lines; *9* — inlet pocket; *10* — runoff tabs; *11* — solenoid; *12* — electromagnetic system power supply; *13* — welding current power supply

level achieved in the weld as a result of high-temperature treatment.

Study [13] generalises the data on control of the hydrodynamic situation in the metal and slag pools by using the natural and external magnetic fields. It is shown that the electromagnetic forces have a decisive effect on hydrodynamics of the weld pool and formation of structure of the weld metal and properties of the welded joints. The methods for exerting the electromagnetic effect in ESW, based on inducing the electric vortex flows or vibration of the melt by using the longitudinal and transverse magnetic fields are suggested on the grounds of the conducted fundamental and applied research (Figure 5).

The effect by the longitudinal magnetic field (Figure 5, *a*) allows an efficient control of formation and detachment of the electrode metal drops. However, a drawback of the method is that it is difficult to induce in the pool the longitudinal field of a sufficient induction, which limits its application for controlling the metal structure. The transverse magnetic fields are more efficient for these purposes (Figure 5, *b*, *c*).

The welding scheme shown in Figure 5, *b* is used for welding with compact welds. In this case the electromagnet coils are mounted on the workpieces welded, which simultaneously perform the function of the magnetic cores. This makes it possible to achieve the high values of induction of the magnetic field in the welding zone. However, this scheme of affecting is hard to implement in welding of large-size parts and parts of a complex configuration.

In welding with the extended welds it is reasonable to use the magnetic system located on opposite sides of the workpieces welded, near the water-cooled shoes, and moving along the edges at a welding speed (see Figure 5, *c*). In this case, interaction of the axial component of the alternating welding current with the constant magnetic field causes vibration of the melt of the weld pool across the edges. Such reciprocating motions of the melt in a two-phase region promote homogenisation and refining of structure of the weld metal. Transverse vibration in the welding gap also adds to increase in penetration of the weld edges, thus allowing the welding energy input to be decreased. A drawback of this method is dissipation of the magnetic field because of a considerable size of the gap between the electromagnet poles determined by thickness of the workpieces welded and water-cooled shoes. Accordingly, efficiency of the electromagnetic effect decreases with increase in thickness of the workpieces.

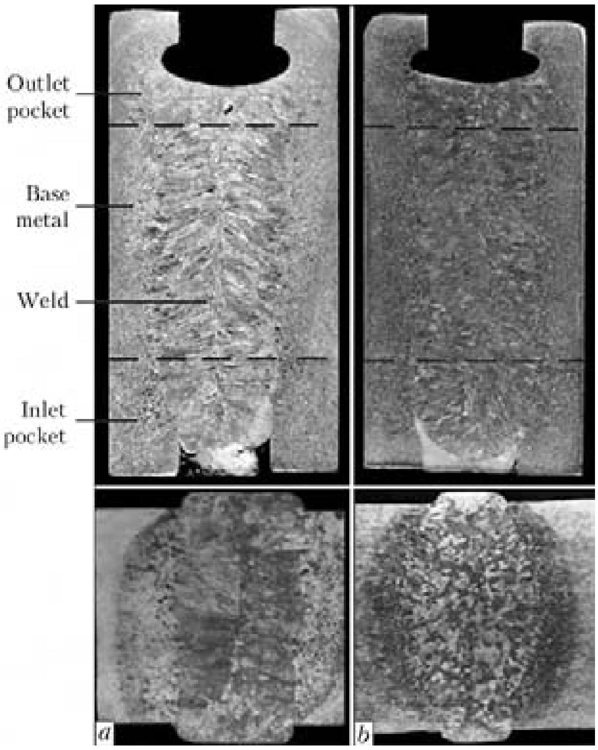

Figure 6. Macrostructure of welded joints on alloy VT1 made without (*a*) and with (*b*) the electromagnetic effect

Later investigations showed a high potential of application of the pulsed magnetic fields for affecting the melt of the weld pool [18]. In this case, coils of the electromagnets are powered by cyclic pulses of the direct current. With this scheme of the electromagnetic effect on the welding melt the possibilities of controlling its hydrodynamics substantially grow. This takes place owing to the possibility of formation of high-power pulses of the magnetic field, as well as owing to restructuring of the hydrodynamic structure of the pool while they are passing. Parameters of the pulses vary over rather wide ranges: magnetic induction of the field – 0.02–0.30 T, pulse duration – 0.3–10 s, and pause duration – 1–20 s. Implementation of this scheme and parameters makes it possible not only to affect the microstructure and chemical homogeneity of the weld metal, but also control its macrostructure (Figure 6).

CONCLUSIONS

Various technological approaches and methods for affecting formation of the weld and HAZ metals in ESW are available now. In a number of cases they are efficient and provide the required properties of the welded joints without postweld heat treatment. Nevertheless, the problems of ensuring the fine-grained, homogeneous structure of the weld metal and decreasing the negative effect of the thermal welding cycle on the base metal remain among the key ones in the ESW technology.

The magnetic field is an efficient tool for control of hydrodynamics of the weld pool and properties of the welded joints. However, the electromagnetic effect on macrostructure of the weld in ESW requires higher power and weight-dimension parameters of sources of the external magnetic fields. This is a serious obstacle for their practical application. Apparently, the topical problems of increasing the efficiency of ESW are development of the methods for intensification of the electromagnetic effect on the weld pool, and minimisation of the devices for controlling solidification of the weld. Further investigations should be aimed at development of the comprehensive methods for controlling the ESW process based on the hydrodynamic and thermal effect mechanisms.

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