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Methods and technologies of electroslag welding with controlled thermal cycle

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Introduction. Improving the quality and operational reliability of welded structures of power equipment is an urgent task of welding production. Its solution is possible on the basis of the development or selection of advanced methods and technologies of electroslag welding (ESW), which eliminate the causes of the formation of tempering cracks (TC) in thick-plate welds. This paper considers a comparative assessment and recommendations on the selection of such advanced ESW methods. The work objectives are to solve the problem of forming a fine-grained, uniform, crack-resistant metal structure of a welded joint with high mechanical characteristics and to reduce the negative impact of the ESW thermal cycle on the base metal. The solution to this problem is possible on the basis of a reasonable choice of methods and technologies for ESW with regulated (controlled) thermal cycle.

Materials and Methods. A comparative analysis of advanced methods and technologies of ESW with a controlled thermal cycle is carried out; a comparison of their pros and cons is provided; practical recommendations on the selection of advanced methods for controlling the thermal cycle parameters are offered.

Results. It is shown that moderate heat input at high-speed ESW in a narrow gap provides a single pass to form a welded joint with a finer-grained structure and high mechanical properties compared to the in-house technologies of ESW and automatic submerged-arc welding. Recommendations for practical use of the method in welding production are given.

Discussion and Conclusions. The results obtained are recommended to be used in the development of ESW technology for thick-sheet welded structures of nuclear and thermal power equipment that enables to abandon post-welding heat treatment (normalization and high tempering).

Keywords: ESW, electroslag welding, slag welding method, thermal cycle of welding, welding joint, narrow-gap welding, structure, properties.

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Introduction. Electroslag welding is a high-performance process for the production of thick-walled welded structures for the power equipment. However, obtaining a homogeneous structure providing high mechanical properties of weld joints is achieved only after complete heat treatment in the form of normalization and high tempering. Moreover, coarse-grained weld metal and heat-affected zone (HAZ) metal has low resistance to cracking during welding and heat treatment in the form of tempering.

The problem urgency is determined by the fact that TC (Fig. 1) are detected unexpectedly at the stage of manufacturing and operation of a welded structure causing emergency situations and significant material costs [1].

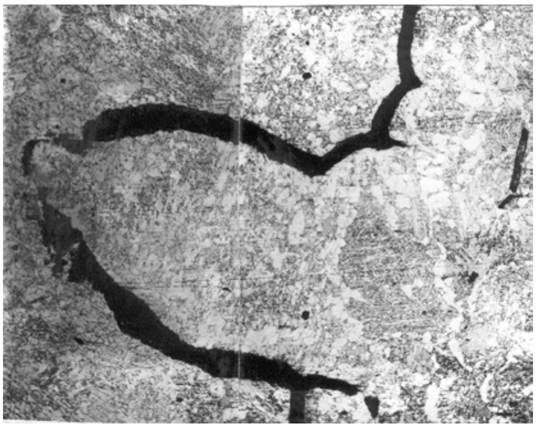


Fig. 1. TC nature in the electroslag weld joint of low-alloy steel, × 100

Studies of national and foreign scientists Eh.L. Makarov, V.N. Zemzin, Yu.V. Poletaev, A.S. Zubchenko, I. Grivnyak, F. Muller, R. Cadman, J. Tanaka, H. Nakamura and others show [2–9] that the tendency to the formation of cracks under welding increases significantly as a result of the combined effect of the unfavorable thermal cycle of ESW and embrittlement of the structure.

Materials and Methods. The developed methods of affecting the ESW thermal regime are based on the regulation of the key parameters of the thermal welding cycle: maximum heating temperature, the metal residence time at a temperature above the temperature of the grain intensive starting, cooling rate, etc. For example, an increase in the cooling rate to form a fine-grained structure of a weld joint can be achieved through introducing additional filler materials into the weld pool: wire, wire bundle, consumable tip, granular metal filler, metal powder, etc. A similar effect can be achieved under concomitant heating of the weld metal and HAZ for local continuous normalization. An increase in the quality and technological strength of the weld metal under ESW is achieved with the use of fluxes with reduced basicity index [10−11]. The method of weld metal exposure to external magnetic fields should be considered efficient.

The solution to a wide range of problems, of which the ESW technology is summarized, is associated with the properties of the slag and metal baths, as well as with the possibilities of controlling the crystallization of the weld using the magnetic hydrodynamic (MHD) flows generated in it. The nature of MHD flows depends mainly on the electric current passing through the melt, and the magnetic fields interacting with this current. The application of controlled MHD flows provides improving the quality, mechanical properties and technological strength of weld joints through optimizing the shape of the metal bath, refining the metal structure and increasing the resistance against the formation of TC. Higher values of plasticity and impact toughness of the metal obtained using controlled MHD flows made it possible, in a number of cases, to exclude post weld heat treatment.

Research Results. Electromagnetic stirring of liquid metal is carried out using magnetic fields generated by a solenoid or electromagnets (Fig. 2). This field interacts with the molten weld pool and regulates the thermal regime of the weld metal. In this case, a decrease in the heat input under welding, the residence time of the crystallizing metal above the temperature of the grain intensive starting, the size of dendrites.

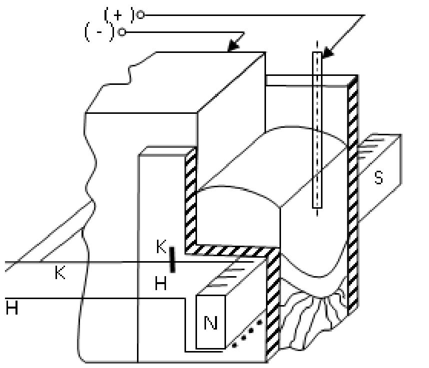
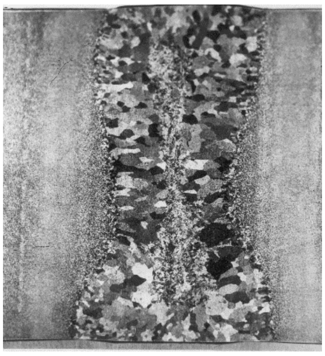


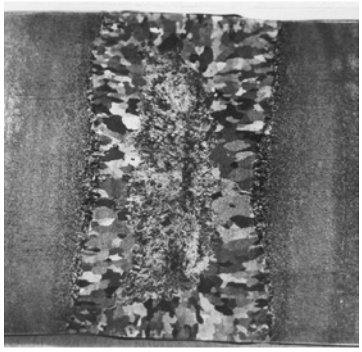
Fig. 2. Scheme of ESW with electromagnets mounted on formers [1]

[1] Poletaev VYu. Methods for improving quality of weld joints made by electroslag welding (review) In: Proc. 5th Int. Sci.-Pract. Conf. on Actual problems of science of the 21st century. St.Petersburg: Cognitio. 2015;2:131–139. (In Russ.)

In Fig. 3, you can see the difference in the macrostructure of weld joints made according to the standard ESW technology and under the magnetic field effect. It should be noted that in the case of standard technology (Fig. 3 a), the average thickness of the weld and its width are much smaller than when exposed to a magnetic field. The area of large overheated grain in the HAZ is the largest and reaches 5−7 mm. For comparison, its surface size does not exceed 1–2 mm, and the zone of large columnar crystals reaches almost the middle of the seam. Therefore, in the central part of the seam, the area of relatively small equiaxed grains has a length of only 3−4 mm.



a)



b)

Fig. 3. Macrostructure of electroslag weld joint made according to standard technology (a) and under impact of magnetic field (b), × 100

Under the magnetic field impact, there is a noticeable improvement in the macrostructure and, first of all, a decrease in the zone of large columnar crystals (Fig. 3 b); the zone of relatively small equiaxed crystals in the center of the weld has a length of 25−30 mm, which is more than 50% of the weld width. For an AN-8 submerged-arc weld joint, this zone is somewhat smaller and amounts to 16−20 mm. In all samples, the size of large columnar crystals of the weld metal reaches 10−11 mm. A decrease in the size of the zone of large columnar crystals should contribute to an increase in mechanical and, above all, plastic properties[2].

The principle of the high-speed ESW method is to programmatically change the current lead points to the electrodes and welded edges with a specified frequency (Fig. 4).

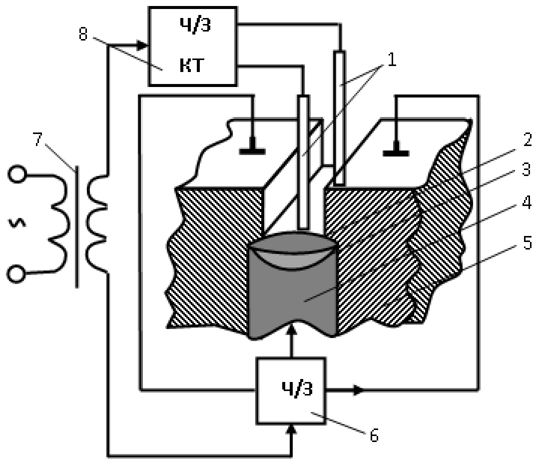


Fig. 4. ESW circuit with switching current leads: 1 — electrodes; 2 — slag bath; 3 — metal bath; 4 — weld seam; 5 — product; 6 — three-channel current changer; 7 — power supply; 8 — two-channel current switch

Switching current leads during welding causes periodic changes in the direction of the electric current lines in the weld pool [12]. At the same time, the motion pattern of the slag-metal melt and, accordingly, the temperature balance in the bath changes sharply. Most of the energy is used to melt the electrodes, while less is transferred to the base metal. All this increases the rate of melting of electrodes by 3−4 times and minimizes the degree of heat removal to the walls of the base metal. Fluctuations of the liquid phase relative to the solid one reduce the temperature gradient at the interface, stop the growth of crystals, and disrupt the frequency and direction of the

[2] Poletaev VYu. Increase in crack resistance under tempering of weld joints of 15Kh2NMFA-VRV thick plate steel based on development of a single-pass automatic arc welding technology: Cand.Sci. (Eng.) diss. Rostov-on-Don, 2017. 162 p. (In Russ.)

dendritical crystallization. The development of these processes contributes to the formation of a finer-grained structure with high mechanical properties without high-temperature heat treatment.

A.N. Khakimov and his colleagues proposed the ESW method without subsequent heat treatment (normalization). With regard to low-alloy heat-hardened steels, the efficiency of regulating the parameters of the thermal welding cycle through reducing the heating time $t_{н}$ and increasing the cooling rate $w_{о}$ is shown. When welding, the parameters of the thermal cycle are controlled by accompanying cooling according to the optimal program. Special technological equipment provides the supply of a cooling water-air mixture to the weld seam and HAZ of the joint using slotted air-hydraulic nozzles installed inside the welding machine at the level of the molten metal pool. Intensive heat dissipation to provide the required parameters of the thermal cycle over the thickness of the metal is carried out from one surface of the weld joint.

Studies on the weld joint metal microstructure have shown that under ESW at a cooling rate of 0.7−1.0° C/s, a ferrite-pearlite structure of the weld and HAZ metal is formed, such as Widmanstätt. Significant precipitation of ferrite along the boundaries of primary austenite grains is observed. The grain size corresponds to a score of 0−1. The ferrite content in the weld metal structure is about 60%, and in the HAZ metal structure – 40%. At a cooling rate of 6 − 8° C/s, the residence time above the temperature of the critical point Ac3 is reduced from 140 to 40−45 s. This contributes to a decrease in ferrite the content in the structure of the weld joint and an increase in mechanical properties.

All of the above welding methods do not completely solve the main problem of overheating and a decrease in the technological strength of thick-plate welded joints in ESW. One of the methods that reduce heat input, and, as a consequence, the grain size and the length of the heat-affected zone, is the method of single-pass electric-arc narrow-gap welding with PF constraint shaping of the weld (Fig. 5). The method is developed by a group led by Yu. V. Poletaev. The thermal welding cycle is regulated through changing the parameters of the electric arc process mode. This is where the proposed method is fundamentally different from ESW.

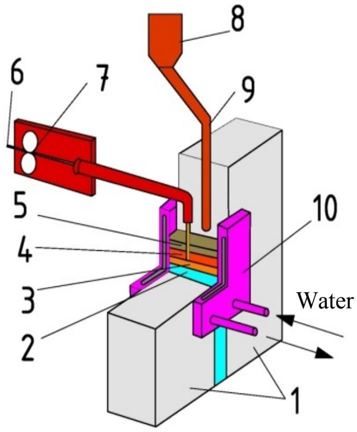
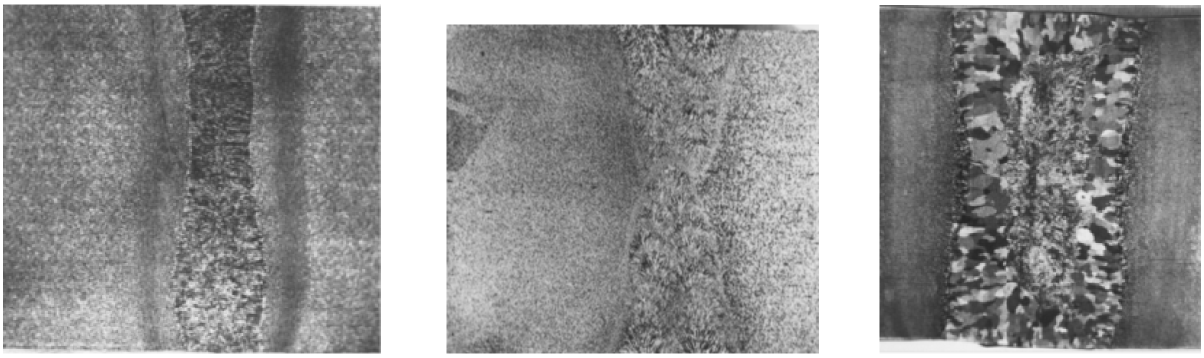


Fig. 5. Basic diagram of the welding technique: 1 — parts to be welded; 2 — weld metal; 3 — welding pool; 4 — liquid slag; 5 — flux envelope; 6 — welding wire; 7 — wire feeder; 8 — flux dispenser; 9 — supply of flux to the welding zone; 10 — copper water-coiled dam

The arc process provides the required heat input, high-quality penetration of the welded edges and a “soft” thermal cycle of metal welding in the HAZ. For this, the height of the liquid slag layer covering the welding arc is maintained equal to the width of the welding gap of slotted cutting, which is 14−18 mm. This completely eliminates slag splashing, provides the process stability and the formation of a high-quality weld joint. The height of the slag layer is controlled and maintained by an automatic flux control device. The optimal welding gap depends on the thickness and length of the weldments and is set experimentally with account for the possibility of welding and high-quality fusion of the edges. For welding sheets of heavy thickness, two or more electrode wires of small diameter (2 mm) are simultaneously fed into the gap located one after the other along the cutting axis. Small-diameter wire feed into a narrow gap provides a high welding speed – up to 5 m/h, while under the traditional ESW method, this speed is no more than 0.9−1.0 m/h. The proposed technique increases the weld metal solidification rate, which contributes to the formation of a fine-grained structure and the required level of mechanical properties of the joint (Fig. 6). It is found that weld joints of carbon and low-alloy steels, made through the electric arc slot welding with a heat input $Q_{св}$ up to 15 MJ/m, a favorable macro- and microstructure without large columnar crystals with a minimum length of the area of overheated large grains near the fusion zone (no more 1 mm) is formed. The quality and mechanical properties of such structures meet regulatory requirements.



. *a*) *b*) *c*)

Fig. 6. Macrostructure of weld joint made by the following method:
(a) slot welding; *(b)* automatic submerged arc welding; *(c)* ESW, × 100

In the course of the experimental study, the following advantages of the electric arc slot welding method were established:

— weld joints undergo only high tempering;

— high welding speed (up to 5 m/h);

— fabricability and high quality of joints;

— minimum angular deformations during welding;

— no mechanical processing of preweld edges;

— welding is performed without preliminary and concomitant heating;

— low flux consumption;

— the formation of joints with high resistance to the formation of intergranular fracture under welding and heat treatment (tempering);

— low costs for heat treatment and subsequent mechanical descaling the joints.

Discussion and conclusions:

1. Advanced methods and technologies of electroslag welding with controlled thermal cycle are studied. It is shown that the optimization of heat input (the thermal cycle parameters) under welding provides the control of structural, mechanical homogeneity of the weld joint and its process through.

2. It is shown that the implementation of ESW methods with a controlled thermal cycle is associated with the complication of technology and equipment.

3. Single-pass electric arc slot welding enables to abandon the multi-pass automatic submerged arc welding technique and single-pass ESW, which significantly increases the production cost of the weldments.

4. Directions for further research are associated with the development of competitive, alternative methods of ESW, single-pass electric arc slot welding of thick-walled structures of the power engineering providing a noticeable decrease in heat input during the formation of joints.

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Claimed contributorship

Yu. V. Poletaev: academic advising; basic research concept and the paper structure formulation; definition of research methodology; task setting. V. Yu. Poletaev: organizing and conducting the experimental research. A. N. Gritsyna: collection and analysis of literature data; participation in the research; critical analysis; editing. R. B. Aguliev: literature and patent analysis; participation in the theoretical research; text editing.

All authors have read and approved the final manuscript.