STRUCTURE AND PROPERTIES OF STEEL 35L WELDED JOINTS PRODUCED USING MULTILAYER ELECTROSLAG WELDING

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In multilayer electroslag welding the heat generated in the process of producing each layer effects the earlier welded areas of a groove performing its partial heat treatment and improving its mechanical properties. The aim of the work is the study of effect of thermal cycle on the structure and mechanical properties of welded joint in multilayer electroslag welding using consumable nozzle. The measurements of thermal cycles of the metal of heat affected zone were carried out. To study the effect of self-heat treatment on the structure and properties of welded joints the investigations were carried out including macro- and microanalysis of weld layers and their heat affected zones as well as mechanical tests of the characteristic areas of welded joints. It was found that in the overheating zone of base metal, not exposed to the reheating, the growth of grains reaches N^2 and N^1 according to the GOST 5639–82 and in the zones of reheating (self-heat treatment) – N^7 and N^8. The hardness of metal of layers and areas of heat affected zone exposed to reheating is on average by 20 % lower than that of the areas of heat affected zone with base metal not exposed to reheating. It was shown that in multilayer electroslag welding alternatively from one edge of a butt to another one the volume of self-heat treatment of the layers of multilayer electroslag weld reaches 38.4 %. In multilayer electroslag welding with deposition of layers from the middle of a butt to its edges, the volume of self-heat treatment of the first (central) layer reaches 87 % and the rest (except of the external layers) is 30–43 %. It was established that the width of heat affected zone scarcely depends on specific energy input in the investigated range of its values. 19 Ref., 10 Figures.

Keywords: *multilayer electroslag welding, thermal cycle, self-heat treatment, heat affected zone, mechanical properties, impact toughness*

The quality of welded joint depends greatly on the structure and properties of a weld metal and heat affected zone (HAZ), which are determined by thermal cycle [1]. Except of melting and crystallization of weld metal the change of temperature results in structural transformations, volumetric changes, elastic-plastic deformations of product material, which at unfavorable thermal cycle in HAZ causes arising of brittle hardened structures for carbon and alloyed steels which predetermined the increased tendency of metal of this zone to cracks and brittle fracture of welded joint as a whole [2]. Therefore in welding of carbon structural steels the task is put to produce welded joint of a full strength.

For the thermal cycle of HAZ in electroslag welding (ESW) the delayed heating of this zone, its long exposure at the temperatures of overheating and next delayed cooling in the region of temperatures of pearlite, intermediate and martensite transformations are characteristic [2].

In multilayer electroslag welding (MESW) the heat generated in the process of producing each next layer affects the earlier welded areas of a groove, making their partial heat treatment and improving the mechanical properties [3–5]. The same heat creates the preliminary heating of base metal in not-welded part of a groove and decreases the cooling rate of welded part of a butt, which, as is known, creates favorable conditions for ESW of steels with increased carbon content. The investigations showed [5] that thermal cycles of HAZ metal in MESW have a complicated nature and remind of the thermal cycle of metal in multilayer manual welding [1].

ESW, unlike the known methods of fusion welding, is characterized by the highest heat inputs per a unity of thickness of welded butt [3], which leads to abrupt increase of HAZ width and growth of grains in it, zone of residual stresses and also higher deformations. It considerably influences the accuracy of geometric sizes of a product after its restoration. With increase of thickness of welded metal it is more difficult to minimize the negative effect of mentioned phenomena on the quality of welded joint due to increase of volume of liquid slag and metal pool. Therefore the application of MESW can be considered to be the most preferable process to provide the quality of welded joint especially in repair of expensive large-size products where it is important to preserve their designed sizes [4, 6–8].

It is known that recrystallization of the metal structure during heating to the point higher than the critical ones results in grains refining at the areas of HAZ and weld overheating and also decrease in concentration of alloying elements and impurities at the grain boundaries [9]. In the metal of each previous layer the HAZ from deposition of the previous layer is observed. In the process of producing each next layer the heat, generating in the welding zone produces heat treatment of metal of the previous layer and HAZ [4, 10]. The data about nature of such heat treatment, its influence on structure and properties of welded joints in ESW with plug welds of circular blind holes of 60 mm diameter and 100 mm depth are given in work [5]. It is shown that impact toughness of deposited metal exposed to accompanying normalization is twice increased and overheating area of HAZ exposed to recrystallization increases by 2.5–3 times as compared to deposited metal and HAZ of the last weld which were not exposed to self-heat treatment. At the areas of overheating zone exposed to heating in intercritical range of A_{c1}–A_{c3} temperatures the impact toughness is 1.5 times increased.

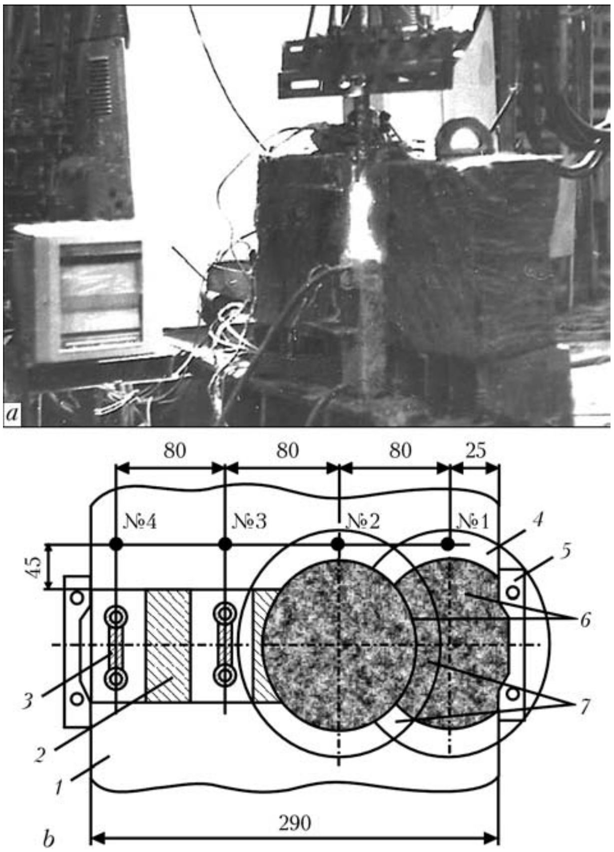

Figure 1. Fragment of measurement of thermal cycles of HAZ metal (*a*) and scheme of thermocouples arrangement in the specimen of steel 34L-ESh (*b*): *1* — edge being welded; *2* — forming plate; *3* — consumable nozzle; *4* — HAZ; *5* — water-cooled cover plate; *6* — layers of multilayer electroslag weld; *7* — zones of reheating (self-heat treatment); No 1–4 are the ordinal numbers of points of thermocouples arrangement

Considering the non-conventional shape of edges preparation for investigated MESW [11] and presence of not one, but two heating centers in a slag pool [12], it became necessary to study the influence of self-heat treatment effect on the structure and mechanical properties of welded joints of the steel 35L. The investigations were carried out including experiments with measurement of thermal cycles of HAZ metal, macro- and microanalysis of layers of welds and their HAZ and also mechanical tests of characteristic areas of welds.

One of the specimens of the size 290 × 940 × × 520 mm of steel 34L-ESh which is widely applied for manufacture by electroslag casting of welded-in bands of rotary furnaces [13], was welded in four passes using two-electrode consumable nozzle. MESW was performed with specific energy E_w = 110–170 kJ/cm^2. Welding up of holes was purposely performed without preheating of specimen. The measurements of thermal cycles were performed according to the method described in work [3], using six-channel self-recording device KSP-4 (Figure 1, *a*). The tungsten-rhenium thermocouples of grade VR 5/20 were used which were mounted along the axes of rectangular holes of edge groove for MESW at the equal distance from the end of one of the edge being welded (Figure 1, *b*). The results of measurements of thermal cycles of HAZ metal are given in Figure 2. The analysis of thermal cycles showed that cooling rates of HAZ metal of each layer in the range of temperatures of 600–500 °C ($w_{6/5}$) do not exceed the critical values for the steel 35L [14] and also decrease with deposition of the layers N (Figure 2, *b*). According to the diagram of the structure components of HAZ metal given in work [15] the danger of martensite formation in this zone is absent. However at the beginning of producing of the first layer, i.e. at the non-steady electroslag process the accelerated cooling of metal occurs which under the conditions of increased rigidity of fastening of edges being welded can result in initiation of cracks-spallings and cracks-tears [10, 16]. The efficient method to prevent such cracks for steels, whose carbon equivalent $C_{eq} >$ > 0.5, is preliminary and concurrent heating of edges being welded up to the temperature of 150–

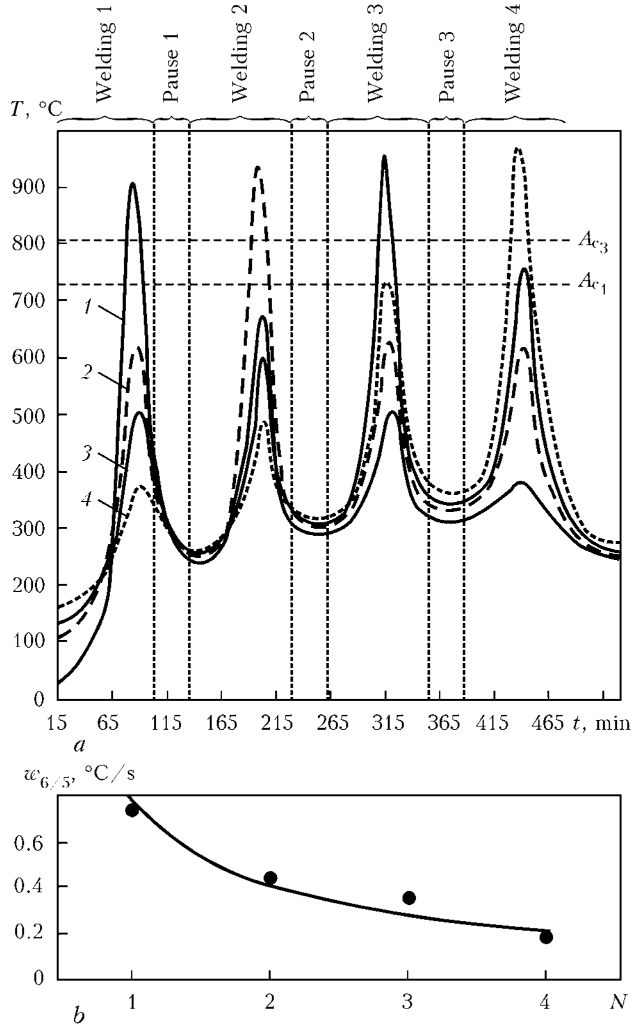

Figure 2. Thermal cycles of HAZ metal in MESW using consumable nozzle (*a*) and dependence of cooling rate of HAZ metal on number of produced weld layers (*b*): 1–4 — thermal cycles of HAZ metal corresponding to the numbers of thermocouples; A_{c1} and A_{c3} are the temperatures of critical points

200 °C [10]. During MESW the concurrent heating of edges being welded can be not performed, as during welding process the periodical heating of a product being welded occurs due to the heat generation in producing of previous layers (Figure 2, *a*).

During analysis the multilayer macrostructure of weld was revealed for which the column crystallization with predominant development of axial crystals is characteristic. In the first layer of weld the fine crystals of small section are detected and also uniaxial crystals are met. In the second layer the crystals are elongated and enlarged ones near the fusion zone. In the third layer the coarser, branchy crystals were detected. In the fourth layer the coarsest branches of crystals are observed. Such structure of crystals is characteristic for electroslag processes. In the investigated case the change of shape of crystals in the succession of producing layers of multilayer weld is caused by gradual heat saturation of specimen and corresponding decrease in speed of cooling of crystallizing metal of layers.

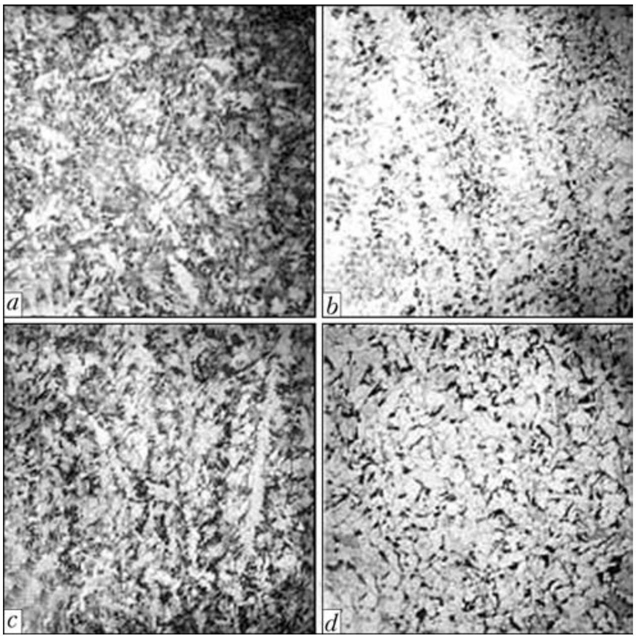

Figure 3. Microstructures (×100) of interfaces of HAZ and deposited metal (steel 34L-ESh): *a*–*c* — of 1st–3rd layers; *d* — metal of 2nd layer exposed to reheating higher than the temperatures of A_{c3} point in making the 3rd layer

The investigation of microstructure of metal of layers of multilayer electroslag welds showed that in the overheating zone of base metal not exposed to reheating, the value of grains reaches N^2 and N^1 according to the GOST 5639–82 (Figure 3, *a*–*c*). In the zones of reheating (self-heat treatment) the growth of grains corresponds to N^7 and N^8 (Figure 3, *d*, Figure 4, *c*).

The analysis of micro- and macrostructures showed that similarly to the data given in the work [5], one regions of previous layers and their HAZ during producing next ones were heated higher than the temperature corresponding to the point A_{c3}, i.e. passed heat treatment as normalization, and other passed heat treatment in intercritical range of temperatures A_{c1}–A_{c3}. For the steel 34L-ESh (analogue of the steel 35L) the temperatures of critical points A_{c1} = 730, A_{c3} = = 802 °C [17]. Therefore the metal of layers and their HAZ, got into the zone of normalization, had to pass the complete recrystallization and have the fine-grain structure [5, 18], and also to possess the improved mechanical properties [10, 18]. In this connection, it is most desirable in MESW to maximum overlap the overheated areas of previous layers by the normalization zone.

To evaluate the effect of self-heat treatment on change of hardness of metal of welded joint, its measurements were made along the overheat areas of HAZ between the base and deposited

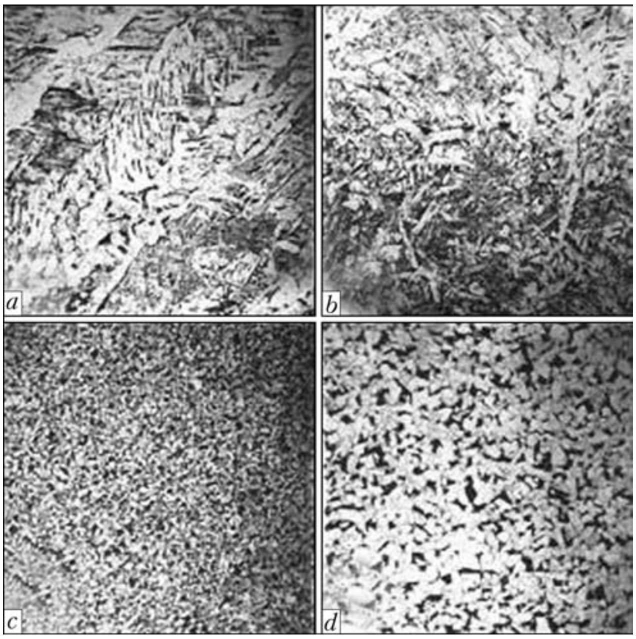

Figure 4. Microstructures (×100) of base and deposited metal of layers of multilayer weld produced using MESW (steel 35L): *a* — deposited metal; *b* — fusion zone; *c* — deposited layer of metal exposed to reheating higher than the temperature of point A_{c3}; *d* — base metal

metal and also centre of deposited metal. The analysis of obtained results showed that character of change of hardness of metal of multilayer electrosalg welds has a common regularity. In Figures 5 and 6 the change of hardness in typical zones of cross and longitudinal sections of multilayer electroslag weld is shown. It is seen that hardness at the overheating area of each layer not exposed to reheating reaches maximum value of corresponding hardness of overheated zone of the last layer (Figure 5, lines of measurements 1, 2 and 7). The areas exposed to self-heat treatment and located at the central part of multilayer weld have the lowest values of hardness, which practically correspond to hardness of base metal (Figure 5, lines of measurements 3–6). The difference between the values of hardness at the area of overheating and central part of deposited metal is amounted, on average, to *HB* 20–30. The hardness of deposited metal in the layers of multilayer weld, exposed to reheating, is changed with the same difference of values (*HB* 5–10) and has the smallest value as compared to the hardness of metal of the last produced layers not exposed to reheating (Figure 6). It was established that hardness of metal of layers and HAZ areas exposed to reheating is in average 20 % lower than that of HAZ areas with the base metal not exposed to reheating.

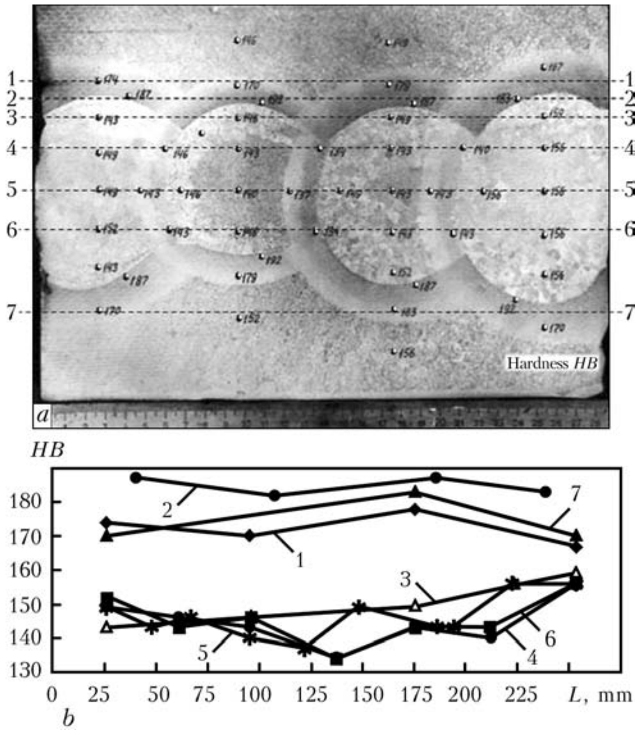

Figure 5. Macrostructure of cross section of multilayer electroslag weld at the depth of 120 mm from the surface of specimen of steel 34L-ESh (*a*) and character of change of hardness along its zones (*b*): 1, 2 and 7 — the lines of measurements of hardness along the zones of overheating the weld layers; 3 — the same in periphery regions of layers; 4–6 — the same in the centre of multilayer weld

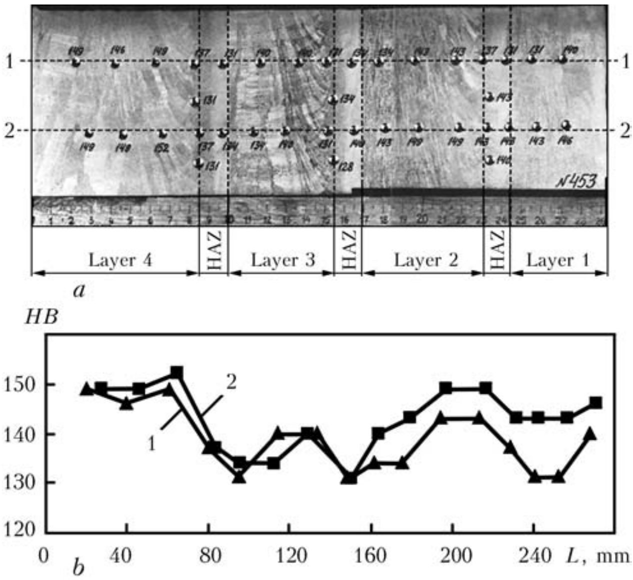

Figure 6. Macrostructure of central part of longitudinal section of multilayer electroslag weld at the specimen of steel 34L-ESh (*a*) and character of change of hardness along its zones (*b*): 1 and 2 — the lines of measurements of hardness; 1–4 — succession of producing weld layers

To determine the mechanical properties of multilayer welded joints of specimens the transverse and longitudinal templates of 50 mm thickness were cut out of the specimens. The specimens to conduct tests of characteristic areas of welded joints for tensile and impact bending tests (GOST 6996–66) were cut out according to the schemes showed in Figure 7. The test results showed that strength characteristics of welded

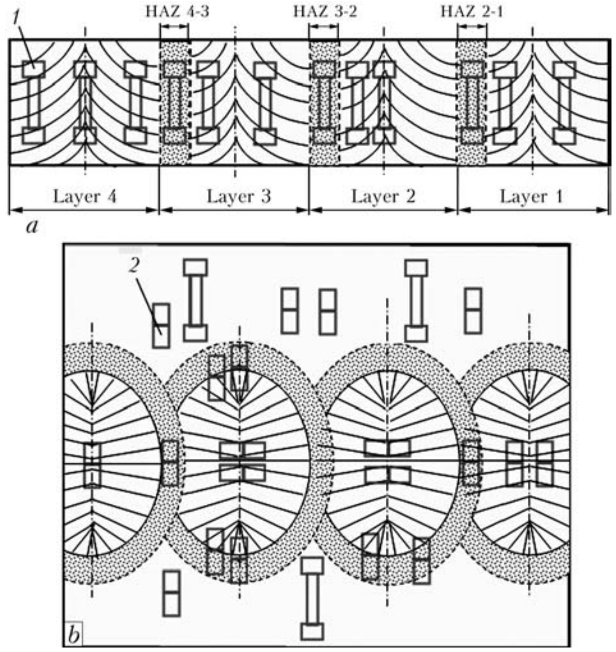

Figure 7. Scheme of cutting out of specimens for conductance of mechanical tests of welded joints produced using MESW: *a* — longitudinal; *b* — cross template of multilayer electroslag weld; 1, 2 — specimens for static tensile «gagarin» and impact bend tests («Mesnager»), respectively

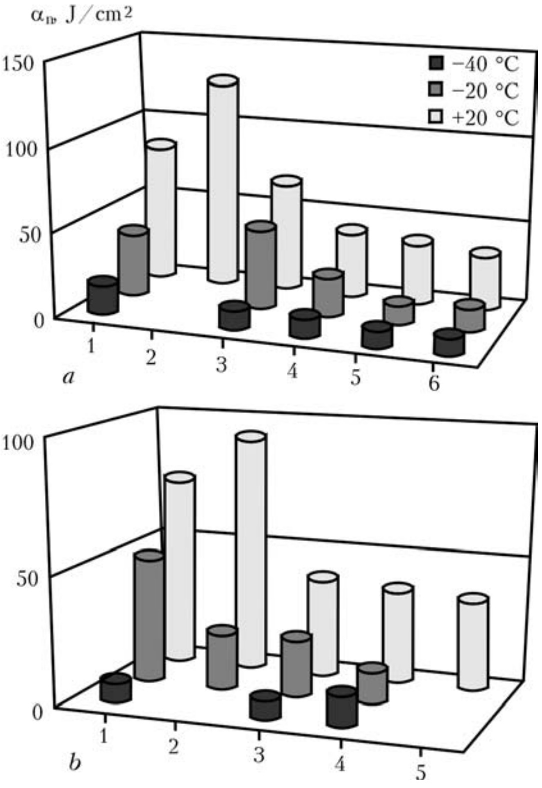

Figure 8. Impact toughness of welded joints and base metal: *a* — steel 35L (1 — deposited metal; 2 — HAZ in deposited metal; 3 — overheating zone at the distance of 0.75–3.0 mm from the fusion line; 4 — normalization zone at the distance of 10–15 mm from the fusion zone; 5 — base metal; 6 — GOST 977–88); *b* — steel 34L-ESh (1 — deposited metal; 2 — HAZ in deposited metal; 3 — normalization zone at the distance of 8–12 mm from the fusion line; 4 — base metal; 5 — TS 22102-61–81)

joints of steels 35L and 34L-ESh, rewelded by MESW, meet, in general, the requirements of standard documents [19]. Ductility of metal of weld layers has an increased values, especially in the zones exposed to concurrent self-heat treatment. The test results of welded joints on impact bending showed the following. The impact toughness α_n in the zones of deposited metal which passed the concurrent self-heat treatment exceeds the values of test results of base metal and also standard requirements by 2–4 times (Figure 8). The values α_n of metal in HAZ of weld layers at the boundary of fusion with the base metal correspond to the test results of base metal.

For quantitative evaluation of self-heat treatment effect on metal and corresponding HAZ of produced layers the measurements of HAZ width and also zone areas after reheating were carried out. The measurements were carried out in the following way. Scanned photos of transverse macrosections were placed on the working table of computer program «KOMPAS-3D V8» observing the scale. Then closed curves of Bezier were plotted following the visually observed lines of fusion and HAZ boundaries by which the areas of investigated regions with the accuracy of 0.01 mm^2 were determined. It was established that in MESW the volume of self-heat treatment of layers of multilayer electroslag weld from one butt to another reaches 38.4 % (Figure 9). In MESW with deposition of layers from the middle of a butt to its edges the volume of self-heat treatment of the first (central) layer reaches 87 % and the rest ones (except the external layers) is 30–43 %. Consequently, to improve the quality

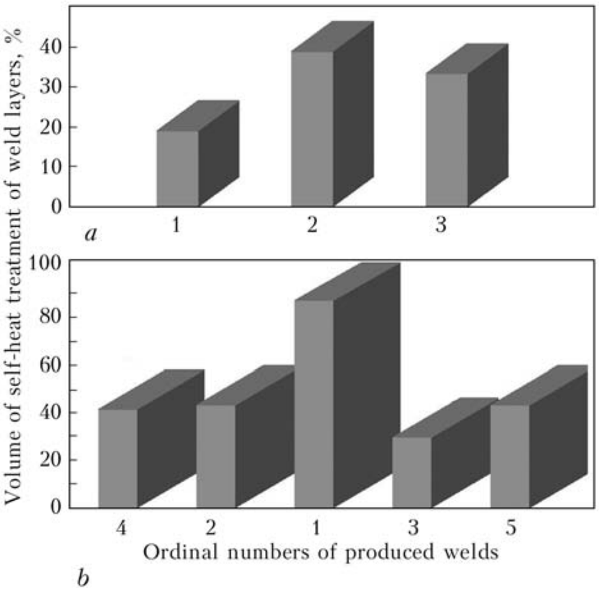

Figure 9. Dependence of volumes of self-heat treatment of layers of multilayer electroslag weld on the sequence of their producing: *a* — successively from one end of butt to another; *b* — the same from the middle of butt to its edges

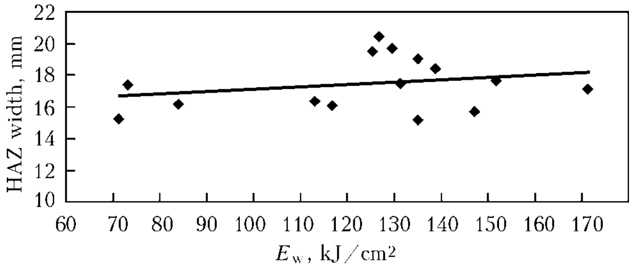

Figure 10. Dependence of HAZ width on specific energy of MESW

of welded joint produced using MESW the most preferable method is random deposition of layers from middle of a butt to its edges.

The carried out measurements showed that the width of HAZ is gradually increased in the direction from the first layer to the last one and reaches 14–20 mm. The width of HAZ of external (the last produced) layers reaches 22.6 mm which is explained by the presence of edge effect [1].

To evaluate the effect of specific energy of MESW on the width of HAZ the dependence was plotted (Figure 10) from which it follows that width of HAZ scarcely depends on E_w in the investigated range of its values. The obtained dependence can be used to predict volumes of self-heat treatment of layers of multilayer weld.

Conclusions

1. It was established that as a result of effect of self-heat treatment of layers of multilayer weld the recrystallization of structure occurs facilitating the grains refining at the area of HAZ overheating and weld layer.

2. Mechanical tests of the characteristic areas of welded joints produced using MESW showed that in these zones the improvement of mechanical properties took place. The impact toughness α_n. in the zones of deposited metal passing the concurrent self-heat treatment exceeds the values of test results of base metal and also standard requirements by 2–4 times. The values α_n of metal in HAZ of weld layers at the fusion boundary with base metal correspond to the test results of base metal.

Thus, in the process of repair of damaged parts at the site of their service using MESW it is possible to be limited by applying a local high tempering, that is most important in making these operations in site-field conditions.

3. The width of HAZ scarcely depends on specific energy input of the process in the investigated range of its values. It was shown that width of HAZ is increased in the direction from the first layer to next ones and reaches 14–20 mm.

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