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INFLUENCE OF EXTERNAL ELECTROMAGNETIC FIELD ON PARAMETERS AND DEFECTS OF CRYSTAL LATTICE OF METAL OF WELDED JOINTS DURING UNDERWATER WELDING

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A study of the influence of external electromagnetic field on the parameters and defects of a crystal lattice (dislocation) in the metal of welded joints of low-alloy steel produced under water was carried out. A mathematical model and software package for calculating density of welding and eddy currents in massive conductors, density of magnetizing currents on the surface of ferromagnetic bodies were developed, mathematical models were used to analyze distribution of electrodynamic forces in arc welding and external electromagnetic influence and evaluation of the developed mathematical models on adequacy and reliability of the obtained results was performed. It was established that an external electromagnetic influence improves the quality of the weld metal, which is very important in welding of critical structures operating in the water environment. It is shown that during underwater welding of joints and applying external electromagnetic influence in the metal of heat-affected-zone, a finer-grained substructure with a general decrease in dislocation density and its uniform distribution is formed. The estimates of the level of local inner stresses taking into account the peculiarities of distribution and dislocation density in structural components show that their maximum level is formed during welding without external electromagnetic influence along the boundaries of upper bainite laths in the places of long dislocation clusters — concentrators of local inner stresses. A low level of local inner stresses is observed in the metal of the welded joints produced on the conditions at application of external electromagnetic influence. This is facilitated by a general decrease in the dislocation density and their uniform distribution in the structural components of a lower bainite, which should provide crack resistance of welded joints. 19 Ref., 1 Table, 5 Figures.

Keywords: underwater welding, welded joints, external electromagnetic influence, microstructure, dislocation density, dislocation hardening, local inner stresses

Currently, underwater electric arc welding is an integral part of any repair or assembly works of metal structures in the water environment. As to the level of mechanical properties, the welds of modern underwater metal structures of critical purpose often should not be inferior to the welds produced on land. At the same time, physicochemical and metallurgical processes during underwater welding proceed in difficult, extreme conditions, which makes it difficult to produce high-quality joints.

One of the relevant and promising methods of improving the quality of welds under water is forced degassing of liquid metal in welding pool, for which external electromagnetic influence (EEI) is used. With the use of EEI the control of movement of liquid metal in the welding pool can significantly improve mechanical and physicochemical properties of welds, increase their corrosion resistance and reduce the level of porosity [1]. The analysis of literature data shows that regardless of the methods and conditions of welding, a certain range of parameters of electromagnetic influence on liquid metal exists, at which the maximum increase in technological and physicochemical properties of welded joints is achieved. Thus, in this range the regularities are revealed, that determine the conditions of EEI optimality.

The need in the technologies of using EEI for liquid metals and alloys determines the necessity of appropriate development of calculation methods and mathematical modeling. Currently, there are different approaches and methods of mathematical modeling for calculation of electromagnetic fields: finite difference method, finite element method, method of integral equations and other that are effeciently used applying computer technologies [2–5].

When modeling the processes that proceed during arc welding using EEI, one of the most important values is the density of eddy currents in massive bodies. These currents significantly affect the magnetic field of the inductor and, as a consequence, distribution of electrodynamic forces in the flows of the pool melt. The arc represents a conical shape conductor, in the

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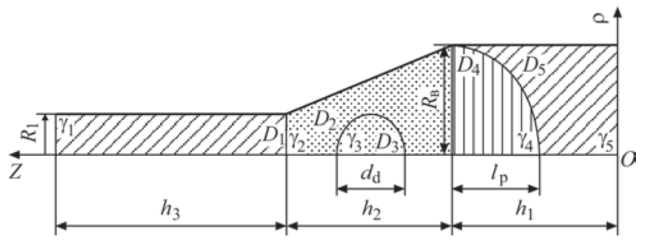

Figure 1. Scheme for calculation (h_1 — material thickness; h_2 — arc height; h_3 — electrode height; R_1 — electrode radius; R_p — pool radius; l_p — pool depth; d_d — drop diameter; D_1 — electrode diameter; D_2 — arc diameter; D_3 — drop diameter; D_4 — pool diameter; D_5 — material diameter; γ_1 — electrical conductivity of the electrode; γ_2 — electrical conductivity of the arc; γ_3 — electrical conductivity of the drop; γ_4 — electrical conductivity of the pool; γ_5 — electrical conductivity of the material)

volume of which there are drops of molten electrode metal. The following parameters are considered to be set: conductivity and shape of plasma, sizes and number of drops, conductivity of drop material and distance between them. The following assumptions were accepted: drops have a spherical shape and welding pool has a hemispherical shape [6–10].

The calculation model is presented in Figure 1.

Based on the model, an algorithm for mathematical modeling of magnetohydrodynamic processes in a liquid metal pool using EEI was developed, which simplifies the calculation process to optimize the technological process.

Moreover, there are several stages of modeling: it is necessary to develop a mathematical model and software package for calculating density of welding and eddy currents in massive conductors, density of magnetizing currents on the surface of ferromagnetic bodies, to apply the developed mathematical models for analyzing distribution of electrodynamic forces in arc welding at EEI, to carry out estimation of the developed mathematical models on adequacy and reliability of the obtained results.

The sequence of all stages of modeling according to the developed algorithm is the following:

1. We set geometric dimensions and electrophysical properties of the system.
2. We set welding current and current in the inductor of external magnetic influence.
3. We solve the system of integral equations and find the distribution of charges.
4. Based on the found we find the components of the field and density of the welding current.
5. We solve the system of integral equations and find eddy and magnetizing currents.
6. Based on the found we find the induction of EEI.
7. We determine the average density of electrodynamic forces for the period.
8. We evaluate the speed of the melt movement and the model correctness.

Based on the proposed algorithm, a special software in Delphi 7 language was developed.

Using the proposed model, it is possible to model different cases of thermophysical parameters of underwater welding. At the same time there is an opportunity to model a variety of options without a large number of options of experimental welding which are rather difficult to be carried out in laboratory conditions.

By conducting a series of numerical experiments, an optimized EEI mode was revealed and a series of experimental welds in real conditions of water environment were performed. The metal structure of welded joints with the use of EEI and without its use was further investigated and X-ray diffraction phase analysis was performed in DRON-1 diffractometer in a cobalt radiation. It was shown that during welding with EEI, in the weld metal and heat-affected-zone (HAZ) there is a BCC-solid solution of α-Fe.

Figure 2 shows the dependence of the parameters of a crystal lattice of solid solutions, which were revealed in the studied areas of the metal of welded joints. The difference between the values of the experimental parameters of a crystal lattice of BCC-solid solutions of the weld metal (Figure 2, *a*) and HAZ (Figure 2, *b*), produced after underwater welding

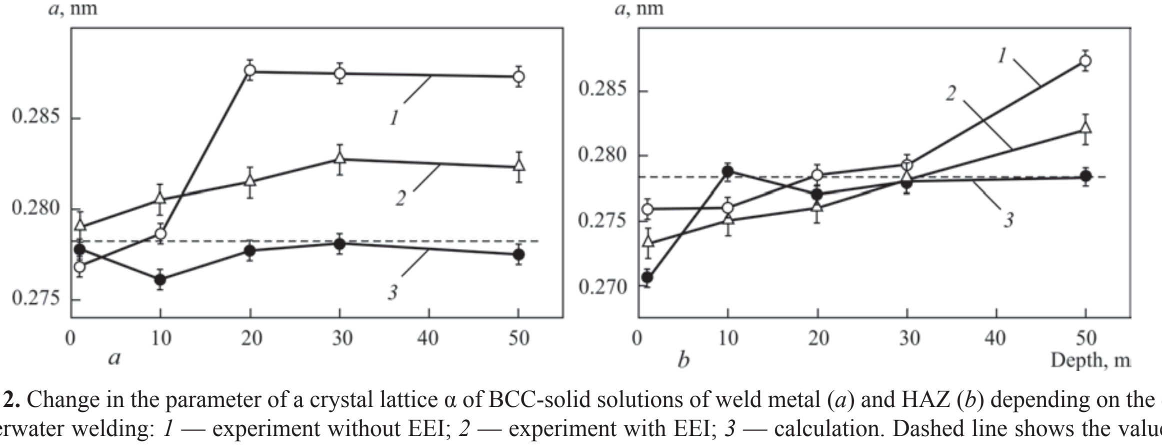

Figure 2. Change in the parameter of a crystal lattice α of BCC-solid solutions of weld metal (*a*) and HAZ (*b*) depending on the depth of underwater welding: *1* — experiment without EEI; *2* — experiment with EEI; *3* — calculation. Dashed line shows the value of a crystal lattice parameter of the weld metal

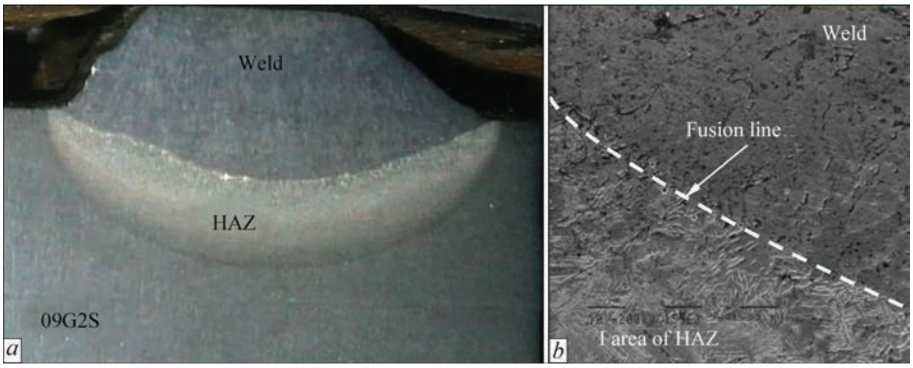

Figure 3. Macrostructure of welded joint (*a*) and microstructure of metal in the area of fusion line and I area of HAZ (*b*, ×1550)

without and with the use of EEI, confirms its effect on formation of the structure.

With an increase in welding depth to 50 m, the parameter of a crystal lattice (*a*) of the weld metal under the condition of using EEI increases slightly (up to 1 %) as compared to the specimens without the use of EEI, where the parameter of a crystal lattice changes more significantly (up to 4 %). In the HAZ (Figure 2, *b*) up to a depth of 30 m, the parameter of a crystal lattice for all cases remains almost the same, but without the use of EEI with an increase in the depth of welding to 50 m, the parameter α increases.

Thus, EEI, which is used in underwater welding, helps to homogenize the metal structure of a welded joint, namely, to reduce the difference as to the parameter of a crystal lattice both between the zones of the welded joint itself as well as between the base material and welded joint. This should provide a uniform level of mechanical properties on the areas of welded joints and its crack resistance [11–16].

The obtained results indicate that the use of EEI reduces the degree of degradation of the weld metal and HAZ structure under the action of water environment and hydrostatic pressure.

It is known that one of the important imperfections of a crystal lattice is its defects — dislocations, around which elastic zones of curvature of a crystal lattice are formed [11–14]. The distribution of dislocations, their density and nature of dislocation structure have an impact on mechanical properties of the metal [5, 12, 17]. When a magnetic field is applied, the dislocation system becomes unstable, which leads to a redistribution of crystal lattice defects and can lead to a mutual annihilation of dislocations and a decrease in inner stresses. Also, point defects can interact with each other. If the vacancy and interstitial atom are joined, then both defects are annihilated, and the atom that was previously interstitial, occupies a normal position in the lattice [18, 19]. Based on the abovementioned, the furhter analysis of processes occurring in the specimens at EEI on the level of fine structure was carried out.

Investigations of the dislocation structure were performed by the methods of transmission electron microscopy (TEM, JEM-200CX microscope of JEOL Company, Japan). As a result of the carried out work, experimental data on the complex of structural parameters formed in HAZ of welded joints of steel 09G2S in the area of overheating were obtained (Figure 3, I area of HAZ). During TEM investigations, the following structures were studied: lower bainite (B_l), upper bainite (B_u) and their parameters — width of lath structures and distribution of dislocation density (ρ) in the structural components.

Detailed studies of the metal microstructure of HAZ overheating area of the specimen using TEM method without the use of EEI showed that the size (width) of laths of an upper bainite (B_u) is 0.2–1.0 μm (Figure 4, *a*, *b*). In the inner volumes of the lath structure of an upper bainite, the distribution of dislocation density is nonuniform. The dislocation density varies from $\rho = (2–4)\cdot10^{10}$ cm^{-2} to $\rho = (5–6)\cdot10^{10}$ cm^{-2} at the maximum values $\rho = (8–10)\cdot10^{10}$ cm^{-2} (Figure 4, *b*). Such dislocation clusters-zones of deformation localization with a higher dislocation density are formed along the coarse-lamellar structures of an upper bainite with a lath size of 0.5–1.0 μm, which are formed in the overheating area at a distance of up to 200 μm from the fusion line. The width of the localized deformation zones is 0.15–0.25 μm. The structure of a lower bainite is more dispersed with a lath size of 0.1–0.4 μm (Figure 4, *c*). The distribution of dislocation density in the inner volumes of the lath structure of B_l has a gradient-free nature at $\rho = (1–4)\cdot10^{10}$ cm^{-2}.

The studies of the specimen with the use of EEI showed that the width of laths of an upper bainite is mainly 0.4–0.8 μm and more dispersed is 0.1–0.3 μm (Figure 4, *d*). In the inner volumes of an upper bainite structure, the dislocation density varies from $\rho = (1.8–2.8)\cdot10^{10}$ cm^{-2} to $\rho = 3\cdot10^{10}$ cm^{-2} (Figure 4, *d*). The structure of a lower bainite (as well as in the specimen without EEI) of more dispersed sizes is 0.1–0.4 μm. The distribution of dislocation density in

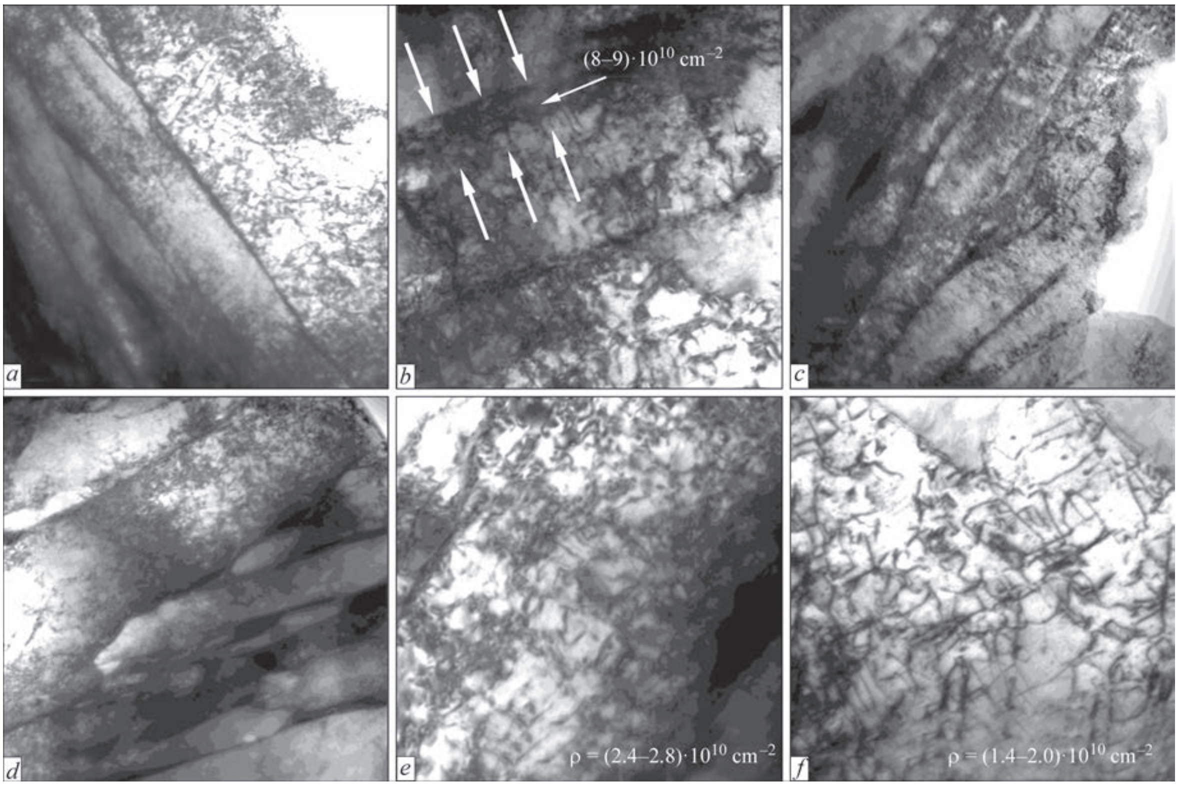

Figure 4. Fine structure of upper (*a*, ×52000; *b*, ×52000; *d*, ×25000; *e*, ×70000) and lower bainite (*c*, ×52000; *f*, ×70000) in the area of overheating of HAZ of welded joints during underwater welding: *a–c* — without the use of EEI; *d–f* — with the use of EEI

the inner volumes of B_l is uniform and varies from $\rho = (1–2)\cdot10^{10}$ cm^{-2} to $\rho = 3\cdot10^{10}$ cm^{-2} (Figure 4, *e*).

Comparing the parameters of the fine structure of the studied specimens, it was found that in the metal without the use of EEI the largest gradients in the size of lath structures of upper bainite and dislocation density are observed, which will lead to a nonuniform level of mechanical properties of the metal, increase local inner stresses and accordingly, reduce crack resistance. In the metal at application of EEI, refinement of the structure at the general decrease and uniform distribution of dislocation density in the volume of structural components is observed that will provide strength and crack resistance of metal.

Therefore, in view of the abovementioned, it appears to be advisable to analyze the dislocation strengthening ($\Delta\sigma_d$) predetermined by interdislocation interaction in the structure of an upper (B_u) and lower bainite (B_l). Quantitative evaluation of dislocation strengthening, according to the theories of deformation strengthening [12–14], was performed according to the following dependence: $\Delta\sigma_d = \alpha Gb\rho^{1/2}$, MPa, [15], where α is the coefficient for steel — 0.5; *b* is the Burgers vector for steel — $2.5\cdot10^{-7}$ mm [12].

Analytical estimates of dislocation strengthening in the structure of B_u show that in the metal of HAZ overheating area during underwater welding without the use of EEI, the following is observed: the largest gradients in dislocation density in volume and along the boundaries of B_u, which lead to 2–3 times increase in a local level of dislocation strengthening from $\Delta\sigma_d = 101$ MPa to $\Delta\sigma_d = 300$ MPa (Figure 5, *a*, Table).

In the metal of the area of HAZ overheating with the use of EEI a uniform distribution of dislocation density is observed, gradients on the dislocation density are absent and, accordingly, the level of dislocation strengthening is uniform ($\Delta\sigma_d$ = 136–175 MPa) (Figure 5, *b*, Table).

The next step in the study of the influence of structure on the properties of welded joints metal was to identify a true real picture of the zones of distributing local inner stresses ($\tau_{i.s.}$), i.e. stress concentrators, the values of these characteristics of the metal state, and the dynamics of their change during underwater welding and the use of EEI. The set problem is of key importance, because the processes of delayed fracture, formation of the source of crack initiation and propagation begin directly from the initiation of inner stress concentrators [16–19].

As far as the distribution and level of local inner stresses and strains can be determined only on the basis of true pictures of the dislocation density distribution, namely this information was provided using the TEM method. Estimation of the level of local inner stresses depending on structural factors was determined on density and distribution of dislocations according to the known dependence for $\tau_{i.s.}$ [19]: $\tau_{i.s.} = Gbh\rho/\pi(1 - \nu)$, where *G* is the shear modulus;

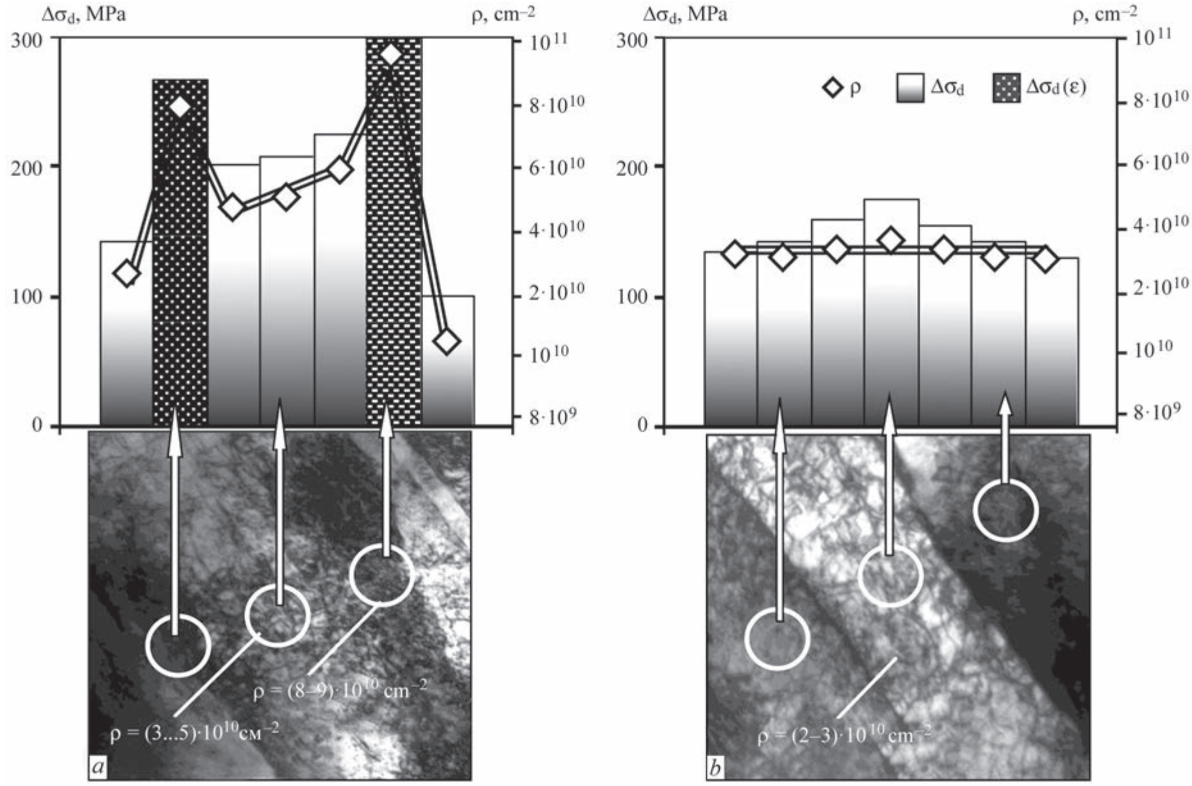

Figure 5. Fine structure of upper (*a*, ×70000) and lower bainite (*b*, ×70000) and, accordingly, change in dislocation density (ρ), dislocation strengthening ($\Delta\sigma_d$) in inner volumes and in the zones of deformation localization (ε): *a* — without the use of EEI; *b* — with the use of EEI

Parameters of fine structure of HAZ metal of welded joints

Parameters	Presence of EEI			
	Without the use of EEI		With the use of EEI	
	Structure			
	B_l	B_u	B_l	B_u
ρ (min), cm^{-2}	(1–2)·10^{10}	(2–4)·10^{10}	(1–2)·10^{10}	(1.8–2.4)·10^{10}
ρ (max), cm^{-2}	(3–4)·10^{10}	(4.5–6)·10^{10} (8–9)·10^{10*}	3·10^{10}	3·10^{10}
$\Delta\sigma_d$ (min), MPa	101–141	141–200*	101–141	136–155
$\Delta\sigma_d$ (max), MPa	175–200	212–245 282–300*	175	175
*In the areas of deformation localization (ε).				

b is the Burgers vector; h is the thickness of the foil (2·10^{-5} cm); ν is the Poisson's ratio; ρ is the dislocation density.

Analytical estimates of the level of local inner stresses show that the maximum values of $\tau_{i.s.}$ = = 1294–1665 MPa = (0.15–0.2)·τ_{theor} (from the theoretical strength) are formed in places of long dislocation clusters — along the boundaries of B_u during welding under water without the use of EEI. This can lead to a decrease in crack resistance and brittle fracture of welded joints throughout the metal of the overheating area of HAZ of welded joints.

Low values of $\tau_{i.s.}$ = 185–554 MPa = (0.02–0.07)·τ_{theor} are typical for welded joints produced under the conditions with the use of EEI. This is facilitated by the reduction in dislocation density with its uniform distribution, which, accordingly, will provide crack resistance of welded joints.

Conclusions

1. Mathematical model and software package for calculating density of welding and eddy currents in massive conductors to optimize the conditions of external electromagnetic influence were developed.

2. The use of external electromagnetic influence reduces the degree of degradation of the metal structure of welded joints under the action of water environment and hydrostatic pressure.

3. In underwater welding, external electromagnetic influence helps to reduce the difference in the parameter of a crystal lattice (α) of the metal along the areas of the welded joint and relative to the base metal.

4. Applying the method of transmission electron microscopy, the structural-phase changes in the metal of the HAZ overheating area of low-alloy steel joints during underwater welding without the use of external electromagnetic influence and during its application were studied. It was established that the structure of a lower and upper bainite, formed in the metal of the HAZ overheating area differs in the parameters of such structural components as sizes of the lath substructure, distribution and dislocation density.

5. During underwater welding without the use of external electromagnetic influence, the structure of an upper bainite has mainly a coarse-lamellar nature at a general increase in the dislocation density and its nonuniform distribution both in the volume as well as along the boundaries of the laths in the zones of a localized deformation. This leads to an increase in dislocation strengthening in the local areas of the structure in the location of long dislocation clusters, and, accordingly, a nonuniform level of mechanical properties and the formation of concentrators of local inner stresses.

6. At external electromagnetic influence in the metal of a heat-affected-zone, substructure refinement, redistribution of defects of a crystal lattice (dislocations) at a general decrease in dislocation density and its uniform distribution is observed. This contributes to a uniform level of strengthening, decrease in the level of local inner stresses in the volume of structural-phase components of the metal and along their boundaries and provides crack resistance of welded joints during underwater welding.

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