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MODELING THE ACTION OF ELECTROMAGNETIC FIELD ON THE STRUCTURE FORMATION OF JOINTS WELDED UNDER WATER

S.Yu. Maksymov, O.M. Berdnikova, O.O. Prilipko, T.O. Alekseyenko, Ye.V. Polovetskyi and **A.A. Radzievska**
E.O. Paton Electric Welding Institute of the NAS of Ukraine
11 Kazymyr Malevych Str., 03150, Kyiv, Ukraine. E-mail: office@paton.kiev.ua

In the developed computer application Proj5.exe the idea of a sequential calculation of values is realized, where the value of welding current/voltage and current/voltage in the inductor of external electromagnetic action is selected by the researcher. This allows increasing the efficiency of research works with a minimum number of underwater experiments. Using the obtained parameters of the external electromagnetic field, underwater deposits were performed on a plate of a low-alloy steel 09G2S using PPS-AN1 flux-cored wire. The studies showed that the use of external electromagnetic action facilitates a refinement of the grain structure of the deposited metal and reduction in the share of nonmetallic inclusions at their noticeable dispersion. In addition, in the metal of the heat-aftected-zone, the parameters of a package structure of bainite decrease and a more uniform level of microhardness during refinement of the substructure is observed. The external electromagnetic field significantly affects the dislocation structure of the metal, contributes to its uniform and gradient-free distribution, which causes a uniform level of dislocation strengthening in the local volumes of the structure and a decrease in the level of local inner stresses. 11 Ref., 7 Figures.

K e y w o r d s : underwater welding, welded joints, low-alloy steel, external electromagnetic action, microstructure, microhardness, lower and upper bainite, dislocations, local inner stresses

The requirements to the quality and reliability of welded joints produced and operated under water are constantly growing. Physicochemical and metallurgical processes during underwater welding take place in difficult, extreme conditions, which predetermine the complexity of the problems of producing high-quality joints. This is associated with intensive heat removal, significant saturation of the molten metal with hydrogen and increased ambient pressure. To intensify the processes of its degassing, reduce the hydrogen content, refine the structure, increase the values of strength and ductility of joints, it is proposed to use external electromagnetic action (EEA) on the melt of the welding pool. The maximum improvement of technological and physicochemical properties of welded joints is achieved in a certain range of parameters of electromagnetic action, which depends on the type of base metal and welding conditions.

It is known that magnetic field has a positive effect on the properties and structure of joints during welding of structural steels. The method of electromagnetic stirring during crystallization of the welding pool was used to create a controlled mode of the process of action at different stages when heat input is present, and when its input into the pool is absent.

Intensive thermodeformation influence on metal, high heating temperatures, nonequilibrium conditions of weld metal crystallization, high- and low-temperature plastic deformation, significant chemical inhomogeneity of the metal affect redistribution of defects of a crystal structure in the weld and heat-affected-zone (HAZ) of a welded joint [1, 2]. Numerous studies showed that the use of any stirring at the stage of crystallization (mechanical low-frequency, vibration, ultrasonic treatment of the melt, etc.) significantly affects the formation of the primary structure, including arc welding. However, from the point of view of the technique of carrying out the process of stirring, the electromagnetic action has an indisputable advantage over other.

When using EEA, the temperature difference on the axis of the welding pool and on its side edges is significantly reduced, and the temperature gradient between the central and peripheral parts is reduced. As a reulst of equalization of average temperatures of the axial and peripheral zones of the welding pool, conditions for crystallization at minimum temperature gradients of the pool are created.

Dislocations are defects in the crystal structure that cause violation of the correct location of atoms. They

S.Yu. Maksymov — https://orcid.org/0000-0002-5788-0753, O.M. Berdnikova — https://orcid.org/0000-0001-9754-9478,
T.O. Alekseyenko — https://orcid.org/0000-0001-8492-753X, Ye.V. Polovetskyi — https://orcid.org/0000-0002-8113-0434

occur during crystal growth and are thermodynamically nonequilibrium. The formation of dislocations can also be caused by the concentration of vacancies, accumulation of impurities and action of high stresses. The process of transforming a cluster of spot defects into linear ones proceeds with a decrease in the free energy of the crystals. Usually the lattice defect increases the inner energy and entropy of the crystal [3]. In addition, the dislocation structure becomes unstable when a pulsed magnetic field is applied. This accelerates the movement of dislocations. The arising spot defects interact with dislocations, which cause their redistribution, and this can lead to a decrease in the inner stresses and mutual annihilation of dislocations.

As was noted earlier, the pulsed treatment leads to refinement of the structure, redistribution of dislocations, dissolution of excessive phases, and a homogeneous distribution of impurity atoms in the metal. All this can not but affect the mechanical properties of the metal [4, 5].

The efficiency of this interaction is determined by the current density in the welding pool, where the process of interaction of magnetic and electric fields is significantly influenced by the physical properties of the water environment. For its specification, it is necessary to determine the nature of distribution of electric current lines in the welding pool, taking into account the conditions of underwater welding. Based on that, it becomes possible to determine the optimal EEA parameters [6-8].

Modeling of technological parameters of welding. In the developed computer application Proj5.exe, the idea of sequential calculation of values is realized, where the value of welding current/voltage and current/voltage in the inductor of external electromagnetic action is selected by the researcher itself.

The whole process of calculations, in the course of which the algorithm is realized, is represented by seven modules, each of which corresponds to its own screen form, where operations are performed in a sequence corresponding to the numbers.

In the first of the modules, data entry and their initial processing are performed. Further, in the module *2*, calculation of the field strength and density of direct welding current is realized. In the module *3*, in all components of arc welding, calculation of eddy currents and magnetization currents generated by the inductor is performed. In the module *4*, the induction of the magnetic field generated by the inductor is calculated. In the module *5*, eddy currents, magnetization currents and charges for sinusoidal welding current are calculated. In the last module *6*, calculation of the field strength and welding current density is performed. The screen form for the module *6* after performing the first *6* envisaged actions is presented in Figure 1.

Microstructure. As a result of a practical experiment by surfacing using flux-cored wire PPS-AN1 on a plate of low-alloy steel 09G2S with a thickness of 12 mm, the welds were produced without and with the use of EEA on the following welding modes: current I = 180–200 A, arc voltage U = 30–31 V, welding speed v = 2.2 mm/s (8 m/h).

Microstructure examinations were performed using the methods of light (microscopes Neophot-32 and Versamet-2, Japan) and scanning electron microscopy (scanning electron microscope SEM-515 from Philips, Netherlands). The microhardness of the met-

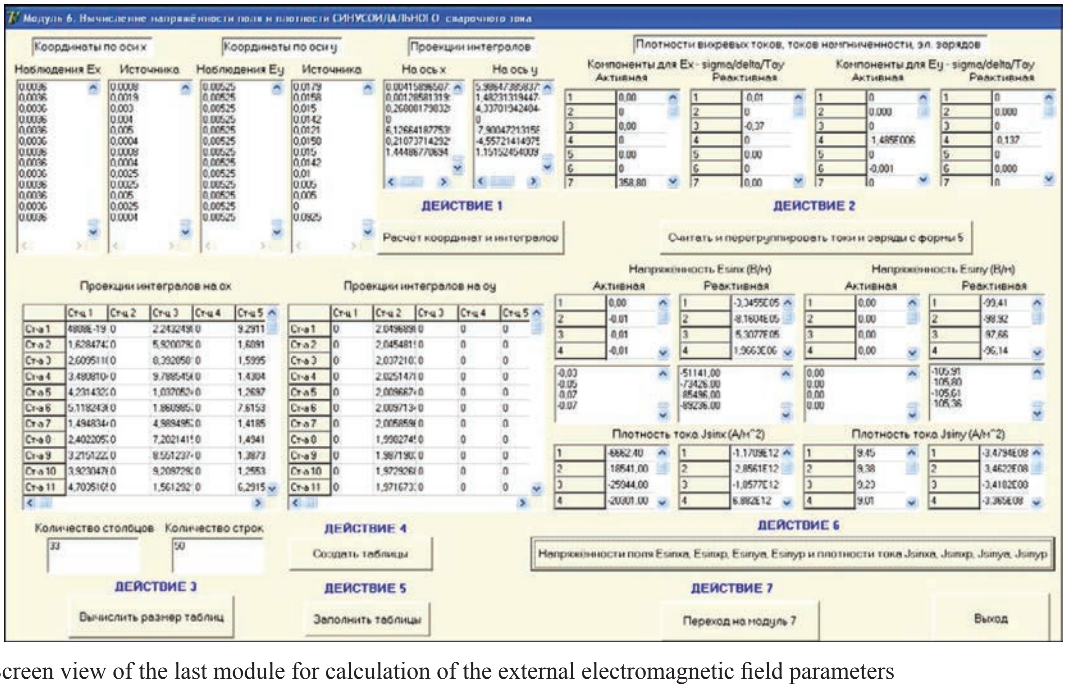

Figure 1. Screen view of the last module for calculation of the external electromagnetic field parameters

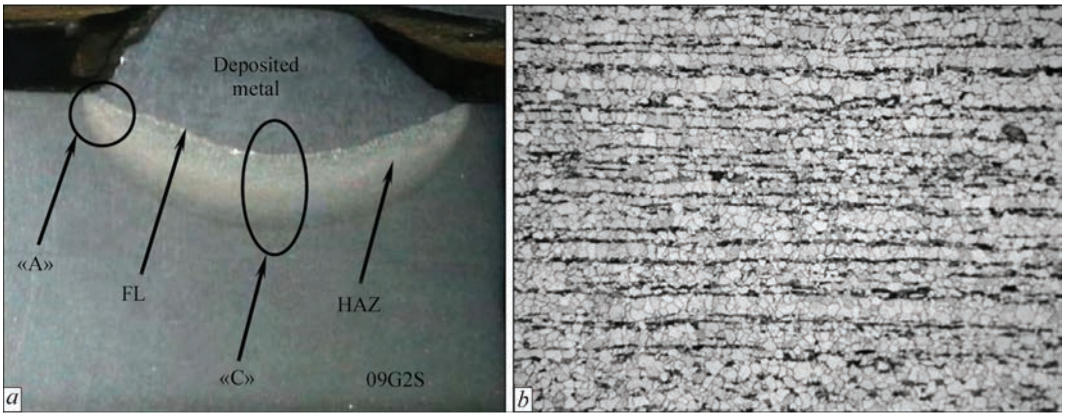

Figure 2. Macrostructure of welded joint (*a*) and microstructure of base metal of steel 09G2S (*b* — ×250)

al was measured in a hardness tester M-400 (LECO, USA) at a load of 0.1 kg. The structural-phase composition, parameters of grain and package structure of the base metal and package structure of the HAZ metal (*D*), welds (l_{cr}×h_{cr}, where h_{cr} is the width; l_{cr} is the length of crystallites), size of nonmetallic inclusions (NI). The following weld and HAZ areas were investigated: overheating (coarse grain — I HAZ), recrystallization (II), partial recrystallization (III), recrystallization (IV HAZ). The study of the structure and microhardness of the metal of welded joints was carried out in several zones («A», «B»), which are shown in Figure 2, *a*.

Metallographic examinations showed that the structure of the base metal of steel 09G2S is ferritic-pearlitic (D_{gr} = 5–10 μm, *HV*–1650–1990 MPa (Figure 2, *b*).

The structure of the deposited metal of the specimens, produced without the use and with the use of EEA, is ferritic and has a size of crystallites l_{cr}×h_{cr} = = 50–150×200–800 μm and 30–80×100–500 μm, respectively, at the same microhardness (*HV*–1700–1870 MPa). In the deposited metal of the specimens in both cases, the formation of NIs of a silicate type of different sizes is typical. In the weld metal without the use of EEA, NIs are large, mainly with a size of 10–60 μm (Figure 3, *a*). With the use of EEA, the number of NIs and their size is significantly reduced (mainly 1–3 μm and single to 10 μm), Figure 3, *b*.

It was established that EEA promotes a refinement of grain structure of the deposited metal and reduction in the share of NIs with their noticeable dispersion, which will provide a high level of mechanical properties of the metal.

Examinations of the HAZ microstructure of the specimens showed that in I; II and III HAZ, bainite structure is formed (lower and upper bainite, Figure 4), and in IV HAZ is ferritic-bainitic.

Without the use of EEA in the zone «A», the size of packages is: D_p = 10–40 μm at *HV*–3220–3830 MPa (I HAZ); D_p = 10–20 μm at *HV*–3660–4010 MPa (II HAZ); D_p = 8–14 μm at *HV*–3220–3660 MPa (III HAZ) and D_p = 5–8 μm at *HV*–2210–2850 MPa (IV HAZ) (Figure 5, *a*). At the transition to a weld root in the zone «B» from I HAZ, coarsening of the package structure to D_p = 30–80 μm at a decrease in microhardness (*HV*–3220–3660 MPa) (Figure 5, *b*) is

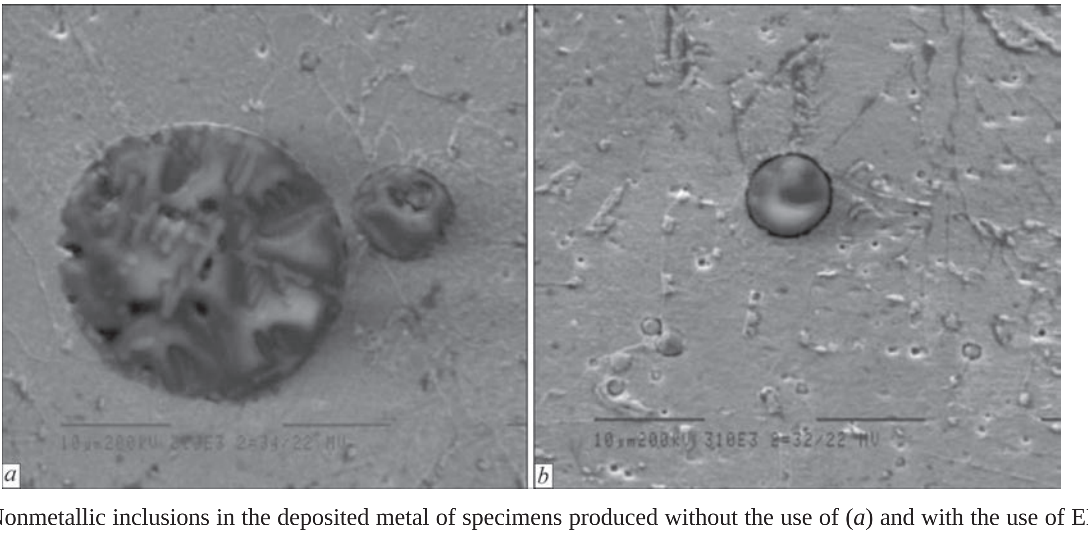

Figure 3. Nonmetallic inclusions in the deposited metal of specimens produced without the use of (*a*) and with the use of EEA (*b* — ×3100)

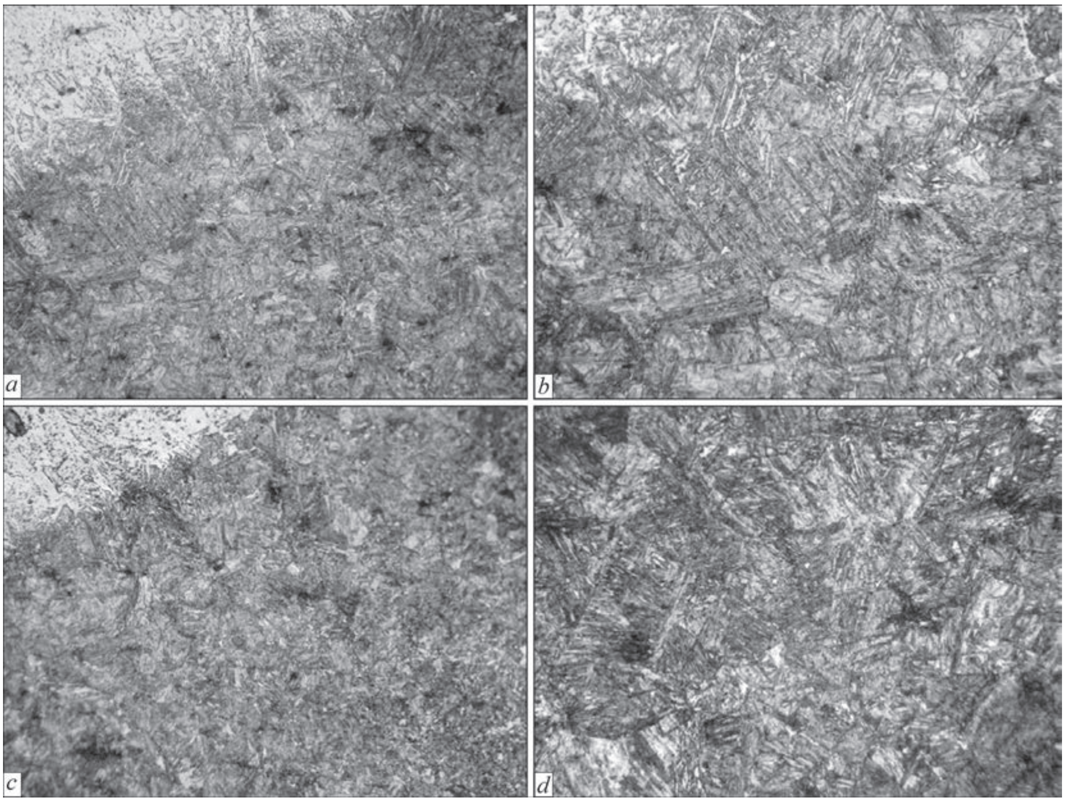

Figure 4. Microstructure of fusion line (*a*, *c* — ×250) and I area of HAZ (*b*, *d* — ×500) of the specimens produced without the use (*a*, *b*) and with the use of EEA (*c*, *d*)

observed. Such gradients on structural parameters can promote arising gradients of properties of the metal strength.

Studies of the specimens produced using EEA showed that the parameters of the package structure of the metal of I–III HAZ decrease: D_p = 10–30 μm at *HV*–3360–3830 MPa (I HAZ); D_p = 10–15 μm at *HV*–3360–3510 MPa (II HAZ); D_p = 8–12 μm at *HV*–3220–3510 MPa (III HAZ), some decrease in microhardness is observed (Figure 5, *c*). At the transition to

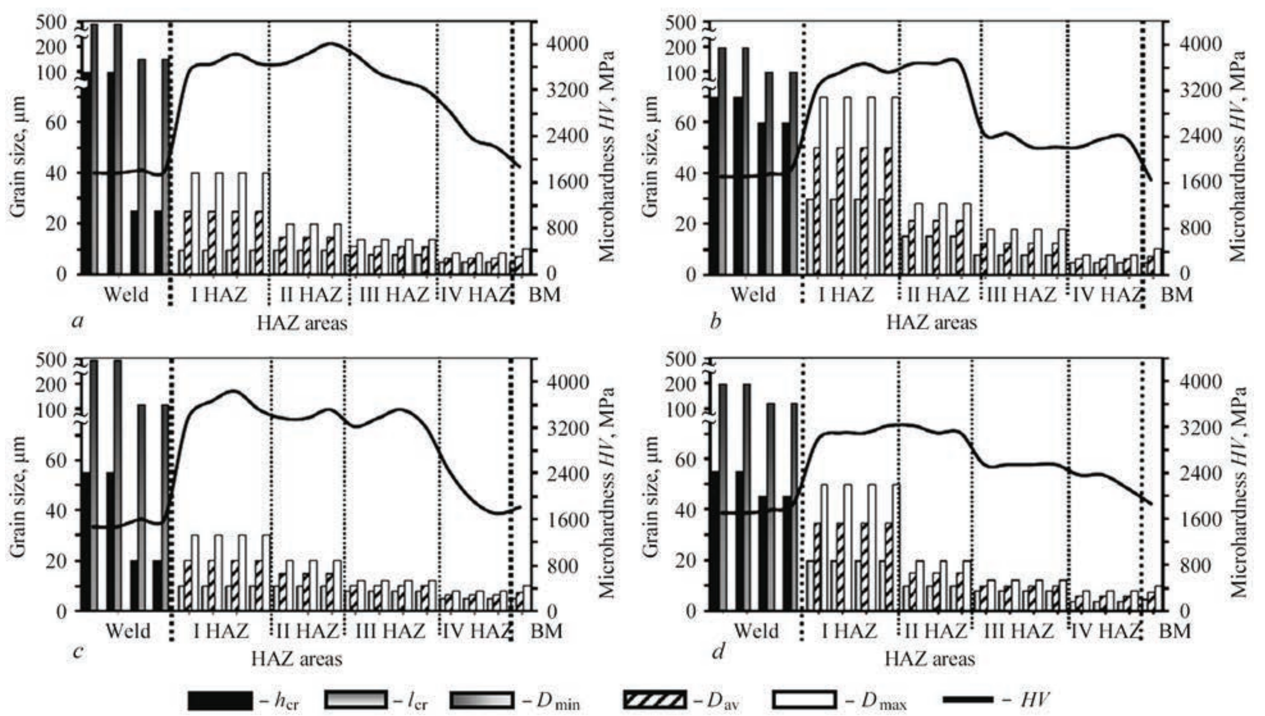

Figure 5. Change of parameters of grain structure — crystallites (h_{cr} — width; l_{cr} — length), packages (*D*), microhardness (*HV*) in the metal of welds and HAZ of the specimens produced without the use (*a*, *b*) and with the use of EEA (*c*, *d*) over the zones «A» (*a*, *c*) and «B» (*b*, *d*)

a weld root (zone «B») from I HAZ microhardness decreases, the structure enlarges, but not so noticeably as in the case of welding without EEA (Figure 5, *d*).

Comparing the parameters of the structural-phase composition of the studied specimens, it was found that in the deposited metal without the use of EEA, large-crystalline ferritic structure in the presence of a significant amount of NIs has mostly a large size, in the HAZ metal, the largest gradients on microhardness and sizes of a package structure of bainitic components are observed (Figure 5, *a*, *b*).

With the use of EEA in the weld and HAZ metal, a more uniform level of microhardness at a structure refinement (Figure 5, *c*, *d*) and the absence of large NIs in the deposited metal is observed, which will provide a more uniform level of the metal strength.

Dislocation structure. Applying the method of transmission electron microscopy (TEM, microscope JEM-200CX by JEOL, Japan), the fine structure of the metal of the specimens with the greatest structural changes — dislocation structure of the metal of the overheating area (I HAZ) was studied in detail. Examinations showed that in the metal of the specimen, produced without the use of EEA, the coarse plate lath structure (lath width $h_l = 0.5$–1.0 μm) of upper bainite (B_u) is characterized by the formation of gradients on the density of dislocations (ρ) from $\rho = (2–4)\cdot10^{10}$ cm^{-2} to $\rho = (8–10)\cdot10^{10}$ cm^{-2} along the boundaries of structural components (Figure 6, *a*).

The use of EEA leads to significant changes in the inner structure of packages of B_u, namely to a uniform redistribution of dislocations with a decrease in their density to $\rho = (1.8–3)\cdot10^{10}$ cm^{-2} and refinement of the lath structure ($h_l = 0.2$–0.8 μm) (Figure 6, *b*).

The structure of lower bainite (B_l) in the HAZ metal of the studied specimens is more dispersed ($h_l = 0.1$–0.4 μm, Figure 6, *c*), the distribution of dislocation density has a gradient-free nature at $\rho = (1–4)\cdot10^{10}$ cm^{-2} (without EEA) and $\rho = (1–3)\cdot10^{10}$ cm^{-2} (with EEA).

As a result, it was found that the use of EEA significantly affects the dislocation structure of the metal, contributes to its uniform and gradient-free distribution [9]. To a greater extent, such structural changes are characteristic for the structures of B_u. In the case of formation of coarse plate structures of B_u with dis-

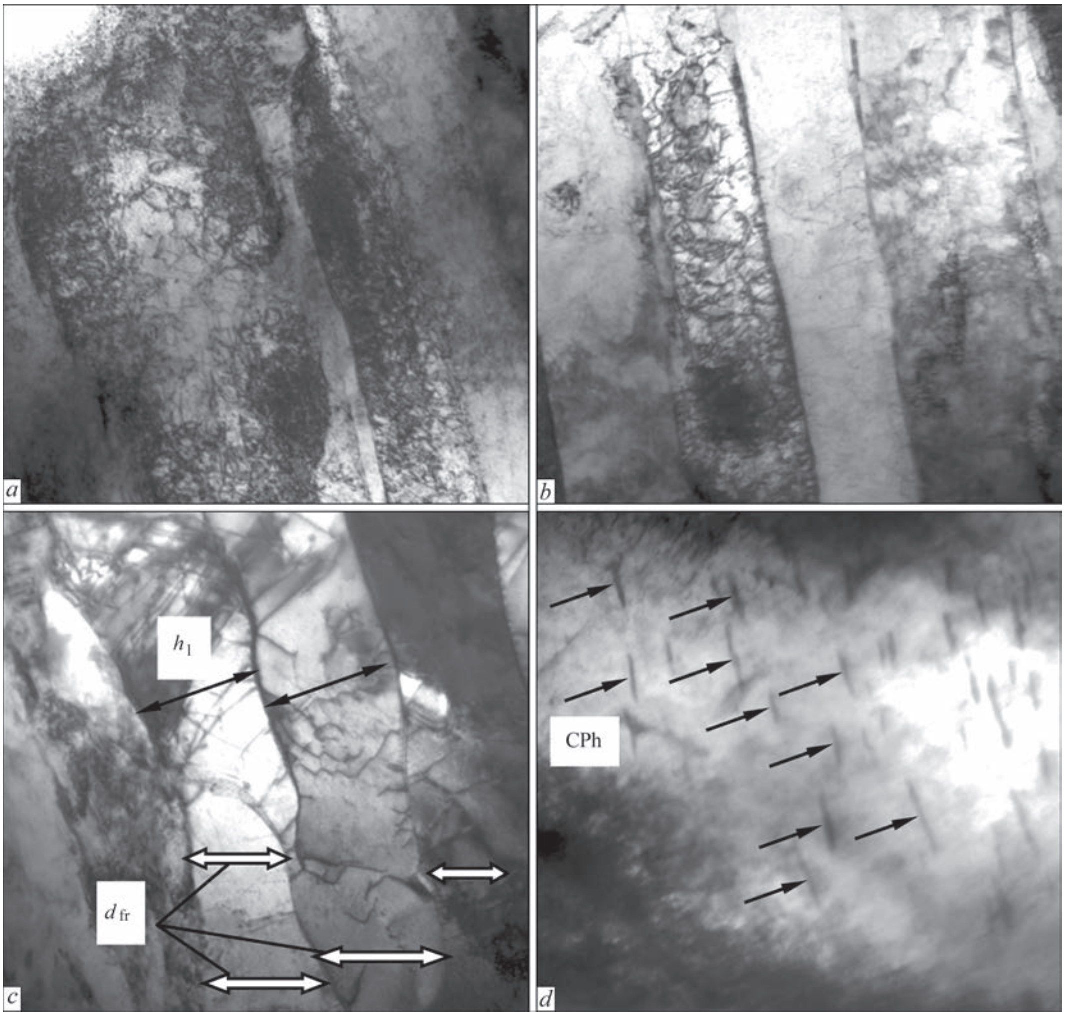

Figure 6. Fine structure of upper (*a*, *b* — ×35000) and lower bainite (*c*, *d* — ×52000) in the area of HAZ overheating of welded joints during underwater welding: *a* — without the use of EEA; *b*–*d* — with the use of EEA

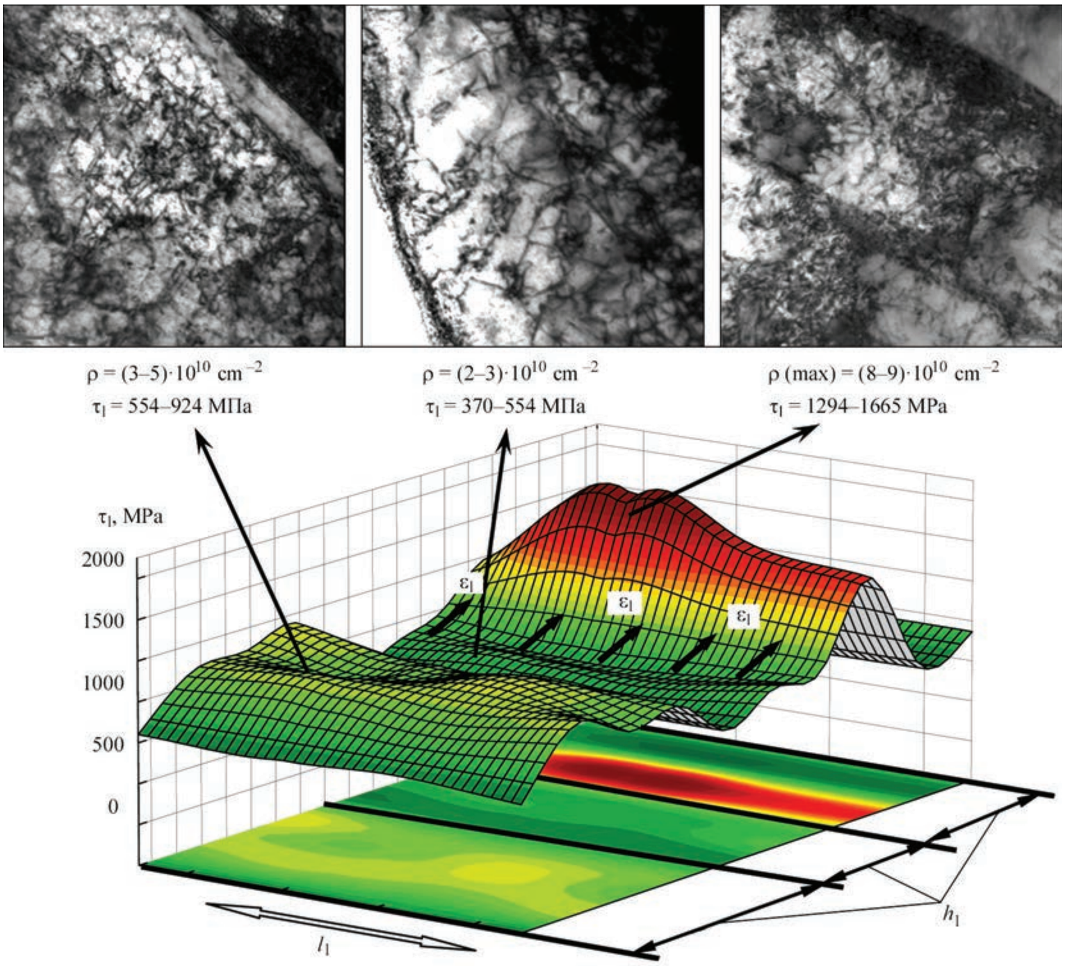

Figure 7. Distribution of local inner stresses (τ_{loc}) in the gradient structural components of the upper bainite (h_l — width, l_l — length of laths) with the zones of localization of deformation (ε_{loc}) in the HAZ metal of the specimen without the use of EEA and the corresponding images of dislocation structures (×70000)

location clusters (without EEA), high density of dislocations, zones of localization of deformation, the level of local inner stresses in the structure increases, which can lead to crack formation (Figure 7).

Taken into account the fact that almost all mechanisms of structural strengthening of the metal are predetermined by interdislocation interaction: in the case of solid-solution strengthening, this mechanism is blocking of dislocations by atmospheres from atoms of impurities and alloying elements; in the case of grain boundary and substructural strengthening, it occurs by distribution of dislocations in volumes and grain boundaries; in the case of dispersion strengthening, it occurs by redistribution of dislocations and their density in the metal matrix saturated with particles of dispersed phases, namely dislocation structure is one of the determining factors that determines the strength and crack resistance of the metal. The lath structure of B_u, which is gradient in size and density of dislocations, will not provide a uniform level of strength and crack resistance of the metal.

In the structural components of B_u with gradients on the dislocation density in the volume and on the boundaries, the local level of dislocation strengthening ($\Delta\sigma_s$) varies from $\Delta\sigma_s$ = 100 MPa to 300 MPa (mode without EEA). In the case of EEA, the gradients on the density of dislocations are absent, which causes a uniform level of dislocation strengthening ($\Delta\sigma_s$ = 136–175 MPa) in the local volumes of the structure [10].

As for the inner structure of the B_l component, a typical feature of underwater welding and the use of EEA is the presence of a fragmented substructure of the size d_{fr} = 0.1–0.3 μm and clear boundaries (Figure 6, *c*). The structure of B_l is characterized by the presence of nanoparticles of carbide phases (CPh), uniformly distributed over the volume with the size 10–20×30–200 nm, the intercarbide distance is 10–70 nm (Figure 6, *d*). Without the use of EEA, the size of the carbide phases is 20–30×50–250 nm, while the distance between the particles increases to 50–80 nm. Such changes in the phase formation processes affect the level of substructural (due to fragmentation) and dispersion strengthening of the metal. According to the Hall–Petch and Orovan dependences [11], the level of substructural ($\Delta\sigma_s$) and dispersion ($\Delta\sigma_{d.s}$) strengthening in the structure of B_l is $\Delta\sigma_s$ = 600 MPa, $\Delta\sigma_{d.s}$ = 628 MPa and $\Delta\sigma_s$ = 750 MPa, $\Delta\sigma_{d.s}$ = 725 MPa in the metal of the specimens produced without the use and with the use of EEA, respectively.

Thus, it was established that the use of EEA provides a refinement of the grain structure of the metal, uniform distribution of dislocations in the inner volumes of the bainite structure, absence of zones of local dislocation strengthening, increase in substructural and dispersion strengthening and reduction in local inner stresses.

Conclusions

1. Mathematical modeling allowed intensifying the research process of underwater welding.

2. In the developed computer application Proj5.exe the idea of sequential calculation of values is realized, where the value of welding current/voltage and current/voltage in the inductor of external electromagnetic action is selected by the researcher.

3. During underwater welding of low-alloy steel 09G2S without EEA and with its use, the deposited metal has a ferritic structure in the presence of nonmetallic inclusions. In the area of overheating (I HAZ), recrystallization (II HAZ) and partial recrystallization (III HAZ), a bainitic and in the area of recrystallization (IV HAZ) ferritic-bainitic structure is formed.

4. It was established that in the deposited metal without the use of EEA in the weld metal, a large-crystalline structure is formed in the presence of nonmetallic inclusions mostly of large size. In the HAZ metal, the highest gradients in the size of the package structure of bainite components and microhardness are observed. When using EEA in the weld and HAZ metal, the structure is refined at a uniform level of microhardness and the absence of large nonmetallic inclusions in the deposited metal.

5. The studies by transmission electron microscopy showed that in the HAZ metal the structure of the lower and upper bainite is formed. The use of EEA leads to changes in the inner structure of the bainite packages of the upper and lower bainite, affects the dislocation structure of the metal, promotes a uniform redistribution of dislocations in the upper bainite at a reduction in their density and refinement of lath structure, fragmentation of the lower bainite. The structure of the lower bainite in the HAZ metal is more dispersed, the distribution of dislocation density has a gradient-free nature in the presence of nanoparticles of carbide phases, uniformly distributed over the volume. Such structural changes provide the absence of zones of local dislocation strengthening, increase in substructural and dispersion strengthening and decrease in the level of local inner stresses.

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JUNE 7, 1977 At the beginning of June 1977, the company «Kemppi» manufactured the first in the world inverter-type power source «Hilarc-250», assembled on the base of the so-called quick-response thyristors. «Quick-response thyristors» allowed converting a direct current into alternating one at the frequency of 2–3 kHz. Thus, the first inverter power sources for welding appeared. Unlike conventional rectifiers, where the transformer operates at an industrial frequency of 50 Hz, in inverter rectifiers it began to operate at a frequency of 2 kHz or higher. The increase in the operation frequency of a welding transformer can significantly reduce its weight and dimensions.