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PHYSICO-MECHANICAL PROPERTIES OF WELDED JOINTS OF HIGH-STRENGTH STEEL WITH THE YIELD STRENGTH OF 690–1300 MPa

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The work is devoted to determination of regularities of influence of features of structural-phase composition (grain, subgrain, dislocation structures, etc.) of metal of welded joints of high-strength steels of different strength class on their mechanical characteristics and crack resistance by determining structural criteria providing the necessary set of these properties. The structure and properties of welded joints of high-strength steels with the yield strength from 690 to 1300 MPa was investigated depending on the rates of cooling and welding, welds alloying, heat treatment conditions and welding methods (mechanized arc, laser, hybrid laser-arc welding): structural low-carbon steels of bainitic-ferritic and bainitic-martensitic type; high-carbon ferritic-pearlitic type; alloy medium-carbon steels of martensitic-bainitic type of a special purpose. The correlation between structural parameters and such a set of properties as strength, fracture toughness, level of localized deformation and local inner stresses in the metal of welded joints was established. It was shown that in compliance with certain ratios of structural-phase components, the characteristics of dislocation and subgrain structure are decisive for providing strength and crack resistance of welded joint metal of high-strength steels. The indices of the level of localized deformation in the metal of welded joints of high-strength steels were obtained and it was found how structural components affect crack resistance of the metal. In order to provide the service reliability of structures in the creation of science-intensive and promising technologies for welding of high-strength steels on the basis of material experimental and theoretical studies, structural criteria were determined to provide the required set of mechanical properties and crack resistance of the mentioned joints. 12 Ref., 4 Figures.

Keywords: high-strength steels, welded joints, structural-phase composition, substructure, dislocation density, mechanical properties, local inner stresses, localized deformation, crack resistance

In different branches of modern industry, including construction, agricultural, transport, machine-building and defense, for the manufacture of welded metal structures, low-carbon, alloy medium- and high-carbon high-strength steels are widely used. At present, the equipment and structures for critical purpose require the use of high-strength steels in a quite wide range of mechanical properties and, accordingly, of different structural and phase composition. Thus, in the construction and transport industries of agricultural purpose, structural low-carbon steels with a yield strength of 350–740 MPa are used. These are steels with ferritic-pearlitic, bainitic-ferritic and bainitic-martensitic structure. The ultimate strength of such steels reaches 490–940 MPa. For high-carbon ferritic-pearlitic steels used in railway transport, this value amounts to 910–1130 MPa and for medium-carbon alloy steels of martensitic-bainitic type of a special purpose, the ultimate strength reaches 1500–1700 MPa. The use of high-strength steels allows not only reducing the weight of structures, but also improving their technical characteristics by providing the necessary set of mechanical properties: high values of static and dynamic strength, fracture toughness and resistance to brittle fracture. Taking into account the fact that many structures made of high-strength steels are structures of a long-term use, it is particularly important to carry out studies of the influence of structural factors on the mechanical properties and crack resistance of the joints of these steels. Most often in the manufacture of the mentioned metal structures, mechanized or automatic welding in shielding gases are used [1–3]. At the same time, such modes of welding are performed, which, on the one hand, would allow providing a high efficiency, and on the other hand, providing a necessary set of mechanical properties and crack resistance of welded joints. Recently, such advanced technologies as laser and hybrid laser-arc welding have been introduced [4], which makes it possible to produce welded joints with much smaller sizes of joints and heat-affected zone and to improve the quality of welded joints and process efficiency as compared to arc welding.

The processes of structure formation in the metal of welded joints of high-strength steels are studied in detail at the PWI of the NASU in the Department of Physico-Chemical Research of Materials, which for many years was headed by Dr. of Tech. Sci., Academician of the NAS of Ukraine G.M. Grigorenko. A

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significant contribution to the determination of structural and phase changes that occur under the influence of welding modes was made by Dr. of Tech. Sci., Prof. L.I. Markashova. Her scientific activity is devoted to comprehensive studies of the structural-phase state of the metal of welded joints of steels, alloys, dissimilar metals and metals with nonmetallic materials, etc. (more than 300 scientific papers.

The main technological works on producing welded joints of high-strength steels with a yield strength ranging from 690 to 1300 MPa was performed in the Department of Welding of Alloy Steels under the supervision of Dr. of Tech. Sci. V. D. Poznyakov, Corresponding Member of the NAS of Ukraine.

The experimental works on the development of new technologies for laser and hybrid laser-arc welding of structural steels were carried out in the Department of Specialized High-Voltage Equipment and Laser Welding under the supervision of Cand. of Tech. Sci. V.D. Shelyagin.

Producing reliable and high-quality welded joints of high-strength steels is an urgent problem, in solving of which it is the most important to conduct a detailed study of the influence of a structural-phase composition and specific parameters of the structure formed in the weld metal and the heat-affected zone (HAZ) on strength and crack resistance of these joints [5–11]. Taken into account that individual areas of the HAZ of welded joints have small sizes, it is not always possible to determine their mechanical properties in the traditional way (mechanical testing of specimens). For this purpose, analytical methods can be used that are based on the results of experimental studies of the structure.

The aim of the work was to determine the regularities of influence of features of structural-phase composition of metal of high-strength steel welded joints of different strength class on their mechanical characteristics and crack resistance by determining structural criteria that provide the necessary set of these properties [12].

The work was performed on welded joints of high-strength steels using different technological parameters of welding modes (cooling and welding speeds, heat treatment conditions, weld alloying). The following three groups of high-strength steels of different purpose and strength class were selected:

1. Structural steels of bainitic-ferritic and bainitic-martensitic type (alform 620M; 17Kh2M; 14KhGN2MDAFB; N-A-XTRA-700) with $\sigma_{0.2}$ = 690–740 MPa and σ_t = 760–940 MPa.

2. High-carbon steels of ferritic-pearlitic type (wheel steel of grade 2; 65G) with $\sigma_{0.2}$ = 785–980 MPa and σ_t = 910–1110 MPa. Studies of wheel steels were aimed at determination of regularities of influence of different technological factors, inherent in the process of restoration of railway wheels by surfacing (surfacing modes, preheating temperature of joints, systems of deposited metal alloying, etc.), on the phase-structural state and parameters of the structure of different areas of welded joints.

3. Alloy medium-carbon steels of a special purpose of martensitic-bainitic type (armor — steel of type 30Kh2N2MF and Miilux Protection 500) with $\sigma_{0.2}$ = 1300–1500 MPa and σ_t = 1500–1700 MPa. The main problems during manufacture of critical welded assemblies and bodies in welding of special-purpose wheeled armored vehicles from heat-hardened high-strength steels is that as a result of welding such steels may soften and in the welded joints cracks may form. To a large extent, the properties of such joints depend on the type of structures which are formed in the HAZ metal during welding. This is significantly influenced by welding modes and cooling conditions of the metal. This study is devoted namely to the issue of a structure formation in the metal of welded joints of such steels.

The investigations were carried out on model specimens-simulators of selected steels produced by thermal welding cycles in the range of cooling temperatures of 600–500 °C at a rate of $w_{6/5}$ = = 2.5–28 °C/s and the joints produced by arc mechanized welding in a mixture of shielding gases (82 % Ar + 18 % CO_2) when using welding wires of the following grades: Sv-10KhN2GSMFTYu, Sv-08G2S, Sv-08Kh20N9G7T, DMO-1G (for structural steels); Sv-08G2S; PP-AN180MN (10KhN2GSMFTYu); Sv-08KhM; Sv-08KhMF (for wheel steels); Sv-10GSMT, Sv-08Kh20N9G7T (for steels of special purpose). Welded joints of steels 14KhGN2MDAFB (Sv-10KhN2GSMFTYu) and N-A-XTRA-700 (Union NiMoCr) were produced by arc welding methods at a cooling rate $w_{6/5}$ = 10–38 °C/s and welding speed v_w = 18–50 m/h (14KhGN2MDAFB); laser welding at $w_{6/5}$ = 28–103 °C/s (v_w = 18–50 m/h, without welding wire); hybrid laser-arc welding at $w_{6/5}$ = 58–63 °C/s (v_w = 72–110 m/h). The mentioned modes of hybrid laser-arc welding provide cooling of HAZ metal in the temperature range of 600–500 °C in a very narrow range, but differ significantly in the parameter v_w.

An approach based on a set of methods of physical materials science was proposed. The microstructure of the weld and HAZ metal were studied by the methods of a light microscopy using Versamet-2 and Neophot-32 microscopes. The microhardness of the metal was measured in a microhardness tester M-400 of LECO Company at a load of 0.1 kg. To reveal grain and dislocation structure, chemical, electrolytic etching methods and the methods of local thinning of specimens were used. During studies, the structures of ferrite, austenite, pearlite, martensite, upper and lower bainite and their parameters like size of packages and grains, as well as the corresponding values of microhardness were investigated. The nature of distribution of chemical elements, as well as fractographic examinations of fracture surface of welded joints were made using analytical scanning electron microscopy (SEM, scanning electron microscope SEM-515 of Philips, Netherlands). SEM examinations studied the nature of metal fracture in fracture zones depending on the load and test temperature, volume fraction of fracture type, size of microelements of fracture surface – facets of brittle or quasi-brittle chip, tough pits, secondary microcracks. Peculiarities of the substructure and distribution of dislocation density in welded joints were studied on thin foils by transmission electron microscopy (TEM) in a microscope JEM-200CX, JEOL Company (Japan) at an accelerating voltage of 200 kV.

Based on experimental investigations at all structural levels of welded joints of high-strength steels, analytical evaluations of strength, fracture toughness, local inner stresses and localized deformation for each class of steels were performed. The structural factors were determined that guarantee the required level of mechanical properties and crack resistance of welded joints. The analytical evaluation of strength was performed taking into account the contribution of each of the structural parameters: sizes of packages, subgrains, lath structure, dislocation density, sizes of carbide phases and intercarbide distances, volume fraction of structures formed in the metal of the welds of high-strength steels. Applying the methods of mathematical processing, taking into account the complex of all structural components and their parameters, the experimental-computational approach of analytical evaluation of strength, fracture toughness, level of local inner stresses and a localized deformation formed in the structure of welded joints of high-strength steels under the influence of thermal welding cycles was improved. The differential contribution to the strength of the structural components of different types of structural hardening was determined: lattice friction, solid-soluble, grain, subgrain, dislocation and dispersion hardening.

The studies of welded joints of structural low-carbon steels showed that under the influence of thermal cycles of arc welding at an increase in cooling rate from $w_{6/5} = 2.5$ to 28 °C/s the nature of transformation of a supercooled austenite in the intermediate region changes, which leads to a change in the phase composition of the metal of welded joints, volume fractions of structural components, increase in microhardness, general refinement of grain and package structure, substructure, increase in a scalar intragranular density of dislocations. It was determined that at equal conditions of ratios of structural-phase components and parameters of grain (or package) structure, characteristics of dislocation and subgrain structures are decisive for providing strength and crack resistance of metal of welded joints of high-strength steels with a yield strength from 600 to 1300 MPa [12].

In the metal of the heat-affected-zone of welded joints of low- and high-carbon steels with ferritic-bainitic and ferritic-pearlitic structure of the base metal, uniform distribution of dislocation density ($(2–4)\cdot 10^{10}$ cm^{-2} $\le \rho \le$ $(7–8)\cdot 10^{10}$ cm^{-2}) during the formation of fine-grained bainitic-ferritic or bainitic-martensitic structures, dispersion of the substructure (to 0.2–1.4 μm) and the presence of 50–80 % of lower bainite provides a high level of strength properties and crack resistance of these joints. In arc welding, this is realized at cooling rates $w_{6/5} = 20–28$ °C/s (for structural ferritic-bainitic and bainitic-martensitic steels) and $w_{6/5} = 5–10$ °C/s (for wheel high-carbon ferritic-pearlitic steels) [12].

While studying welded joints of alloy medium-carbon steels of a special purpose, it was found that the gradientless density distribution of dislocations ($(7–8)\cdot 10^{10}$ cm^{-2} $\le \rho \le 10^{11}$ cm^{-2}) at the formation of the refined structure of tempering martensite with a substructure of 0.4–0.8 μm and a small fraction (5–20 %) of the component of lower bainite, provides high operation properties of the produced joints [12]. Such structural state is provided in cases when during welding the metal of a HAZ cools down at rates $w_{6/s}$ = = 3.8–5 °C/c. The compliance with this fact guarantees the maximum level of fracture toughness and crack resistance of welded joints. It is shown that the highest index of fracture toughness K_{1C} = 110 MPa·m$^{1/2}$ was obtained at $w_{6/5} = 3.8–5.0$ °C/s due to the formation mainly of the structure of tempered martensite with a small fraction of lower bainite (up to 12 %). As the cooling rate increases to $w_{6/5}$ = = 12.5 and 21 °C/s, the value of K_{1C} decreases to 85 and 70 MPa·m$^{1/2}$, respectively. Such a decrease in K_{1C} is associated with a decrease in the fraction of lower bainite, an increase in the fraction of martensite component in the presence of hardening martensite.

In welded joints of medium-carbon alloy steels of special purpose with different systems of alloying of welds, exclusively martensitic structure at the presence of hardening martensite (M_{hard}) at a nonuniform distribution of density of dislocations and its maximum indices ($\rho = (1–1.6)\cdot 10^{11}$ cm^{-2}), formed during welding wires of ferritic-pearlitic type (Sv-10GSMT)

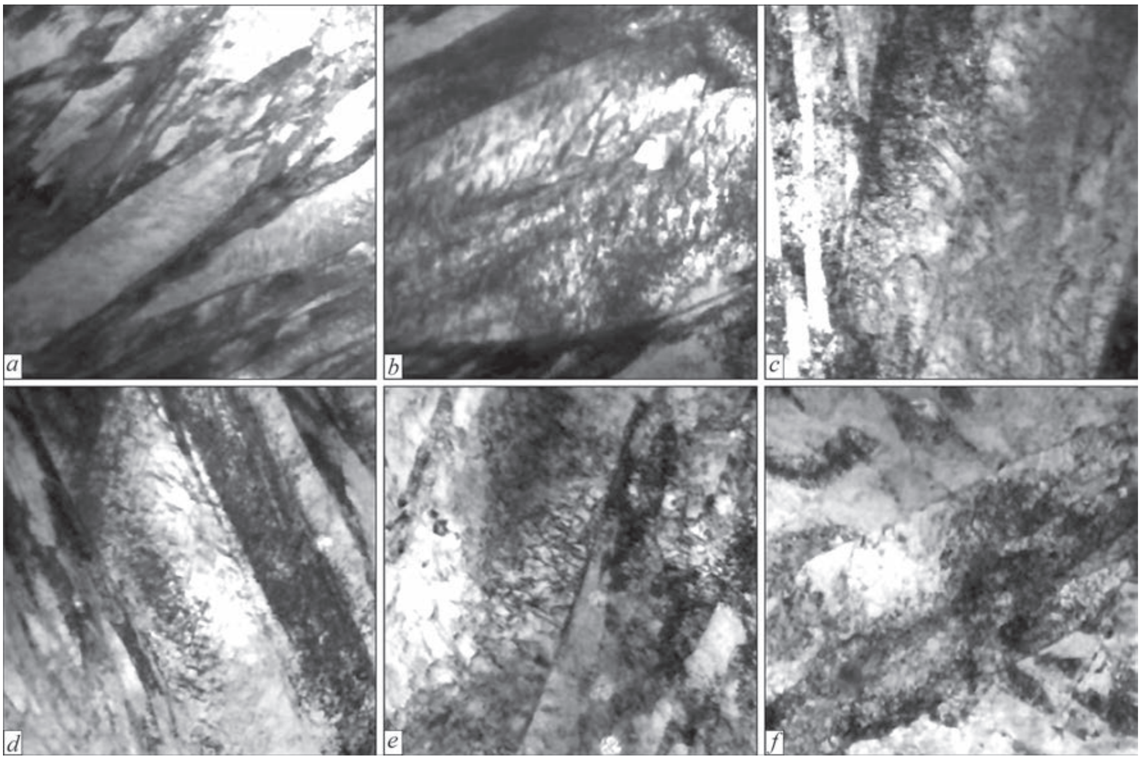


Figure 1. Thin structure of M_{hard} (*a*, *b*), M_{temp} (*c*–*e*) and B_l (*f*) in HAZ metal of welded joints of steel of type 30Kh2N2MF when using different wires: Sv-10GSMT (*a*–*c*); Sv-08Kh20N9G7T (*d*–*f*) after welding (*a* — ×22000; *b*, *d* — ×35000) and LTT (*c* — ×35000; *e* — ×52000; *f* — ×35000)

(Figure 1, *a*–*c*). In the case of austenitic welding material (Sv-08Kh20N9G7T) in welds and HAZ metal, the density of dislocations decreases significantly ($\rho = (8–9)\cdot10^{10}$ cm^{-2}) at its uniform distribution. When using Sv-08Kh20N9G7T, the metal of the near-weld HAZ area has mainly the structure of tempered martensite (M_{temp}, Figure 1, *d*, *e*) with a small share of lower bainite (B_l, Figure 1, *f*). In both cases of welded joints, low-temperature tempering (LTT) leads to a decrease in *HV*, uniform redistribution of dislocations

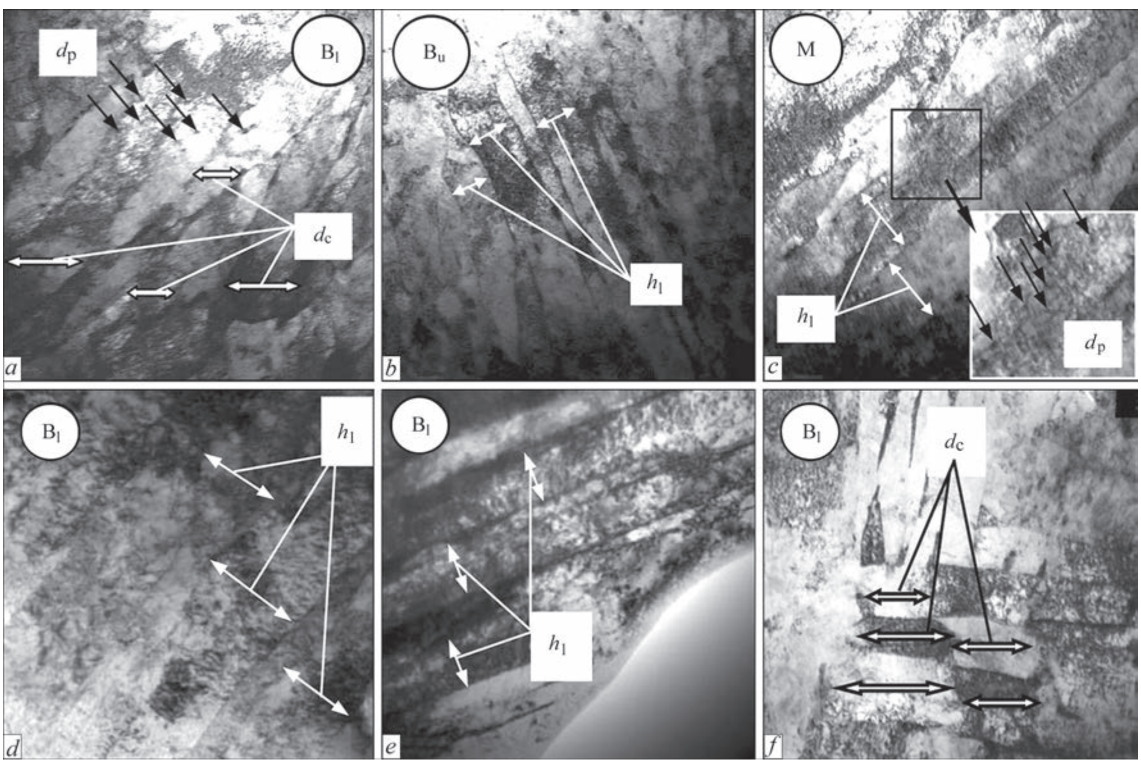
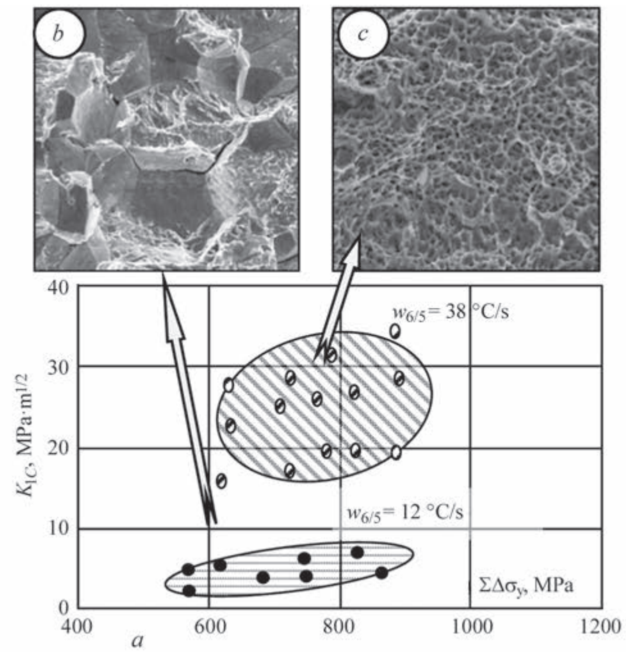


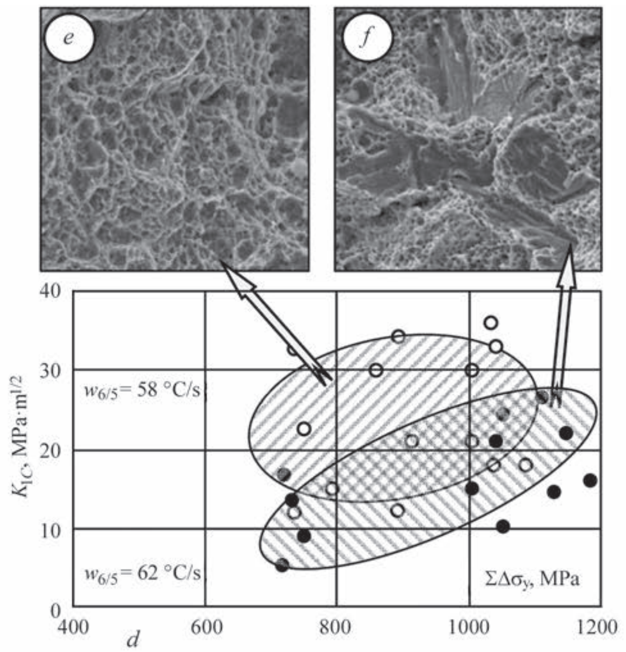
Figure 2. Thin structure of HAZ metal of welded joints of steels N-A-XTRA-70 (*a*–*c*) and 14KhGN2MDAFB (*d*–*f*) in hybrid laser-arc welding ($w_{6/5}$ = 58 °C/s); v_w = 72 m/h): *a*, *d*, *e*, *f* — B_l; *b* — B_u; *c* — M_{temp}, ×25000

and a decrease in their density. To a greater extent, such structural changes are characteristic of the joints produced using Sv-10GSMT.

In the metal of structural low-carbon steels with a yield strength of more than 600 MPa (14KhGN-2MDAFB; N-A-XTRA-70) at high cooling rates in the modes of laser and hybrid laser-arc welding processes, in lower bainite and tempered martensite in the welds and HAZ metal nanostructures are formed [9, 12]. A typical feature of the structure formed during high-speed laser and hybrid welding of high-strength steels during dispersion of laths width (h_l, Figure 2, *a*–*e*) B_l and upper bainite (B_u) is the presence of a fragmented substructure of B_l of the size of 80–300 nm and clear boundaries (Figure 2, *a*, *f*). In this case, both the structure of B_l and M_{temp} are characterized by the presence of nanoparticles of carbide phases. The size of nanoparticles of carbide phases (d_p), uniformly distributed throughout the volume of the structure, is 10–30 nm (Figure 2, *a*, *c*). The formation of the nanostructured state in lower bainite and tempered martensite will increase the strength, fracture toughness and crack resistance of structural steel joints.

With a respective change in the modes of arc, laser and hybrid laser-arc welding of structural steels, the ratio of the components of lower and upper bainite, martensite, their parameters, volume fraction, as well as density and distribution of dislocations change also. Under the modes with a high input energy, the structures of upper bainite are mainly formed at a general increase in the size of grain and subgrain structures





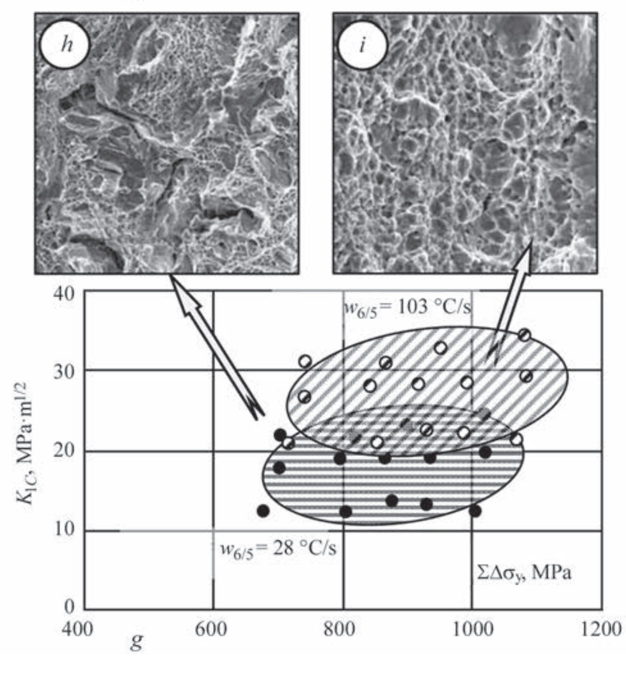


Figure 3. Calculated values of strength ($\Sigma\Delta\sigma_y$) and fracture toughness (K_{1C}) of metal of welded joints produced in different modes: *a* — arc; *d* — hybrid laser-arc; *g* — laser welding and, accordingly, fractograms of the nature of fracture: *c*, *e*, *h* — tough fracture; *b* — brittle intergranular fracture; *f* — brittle intragranular; *h* — quasi-brittle fracture (×2020)

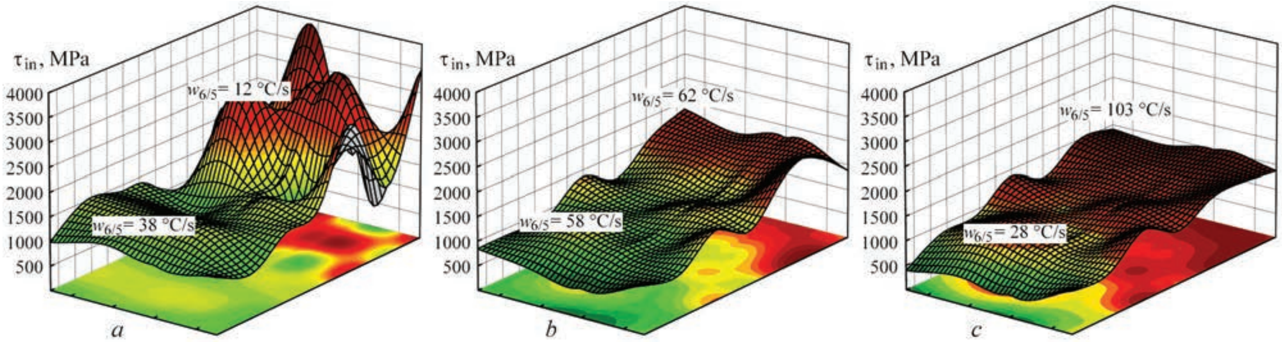


Figure 4. Distribution of local inner stresses τ_{in} in the structure of welded joints in arc (*a*), hybrid laser-arc (*b*) and laser welding (*c*): maximum values of τ_{in} at $w_{6/5}$ = 12; 62; 103 °C/s; minimum τ_{in} at $w_{6/5}$ = 38; 58; 28 °C/s

with a nonuniform distribution of dislocation density (from $\rho = (4–6)\cdot10^{10}$ cm^{-2} to $\rho = (1–2)\cdot10^{11}$ cm^{-2})). A decrease in input energy contributes to the predominant formation of the structures of lower bainite at a significant grain and subgrain refinement with a uniform distribution of dislocation density ($\rho = (6–8)\cdot10^{10}$ cm^{-2})). Such structural changes provide a set of properties of strength and fracture toughness (Figure 3).

Evaluations of the level of local inner stresses (τ_{in}), presented in the diagrams of Figure 4, show the following. Extended zones with the maximum values of τ_{in} (1900–3700 MPa) are formed in the conditions of arc welding at the modes with the minimum cooling rate along the intergranular boundaries of B_u in the places of extended dislocation clusters ($\rho = 2\cdot10^{11}$ cm^{-2}), Figure 4, *a*. This leads to the initiation of microcracks in these areas and, accordingly, to a reduction in the crack resistance of welded joints. A decrease in the values of τ_{in} is characteristic of welded joints produced in hybrid welding (τ_{in} = 1470–1867, Figure 4, *b*) and especially in laser welding (τ_{in} = = 1470–1663 MPa, Figure 4, *c*) which is contributed by the formation of fine-grained structures of B_l in combination with a uniform distribution of dislocation density in the welding zone.

As a result, it was found that the optimal properties of strength, ductility and crack resistance of welded joints of high-strength structural steels are provided in the conditions of arc welding at a cooling rate $w_{6/5}$ = = 38 °C/s, in laser welding at $w_{6/5}$ = 103 °C/s, and in hybrid laser-arc welding at $w_{6/5}$ = 58 °C/s, which is predetermined by the formation of the most dispersed structures: lower bainite, fine-grained tempered martensite in the absence of extended dislocation clusters — concentrators of local inner stresses.

Establishing the regularities of influence of the structural-phase composition of the metal of welded joints of high-strength steels with a yield strength from 600 to 1300 MPa, produced in different ways and using different welding modes on their physical and mechanical properties, allowed determining the conditions under which in the welds and HAZ metal the structures will form that will provide them with the necessary set of mechanical properties and a high crack resistance. TEM examinations established the relationship between the parameters of the formed substructure directly with the dislocation structure, namely with the level of a localized deformation (ε_l) with the fields of τ_{in}, which grow with an increase in ρ [12]. Such evaluations were made taking into account the average distance of dislocation displacement (S, which according to TEM examinations corresponds to the parameters of the substructure) in the process of thermodeformation effect for welded joints of all investigated high-strength steels.

Thus, for lower bainite $\varepsilon_l \le 20$ % at $\rho = (4–8)\cdot10$ cm^{-2} and with the sizes of its substructure being 0.1–0.8 μm. In the strucutre of upper bainite the formation of the zones of a localized deformation in the range of 10 % $\le \varepsilon_l \le$ 70 % at $\rho = (8\cdot10–1.4\cdot10^{11})$ cm^{-2} is typical. The values of the level of deformations in martensitic structures also differ. In tempered martensite it is $\varepsilon_l \le$ 50 % and in hardened one it is 40 % $\le \varepsilon_l \le$ 140 %. It was found that the formation of zones of a localized deformation significantly reduces the crack resistance of metal in the range of 50–140 % at $\rho = (1.1–2,0)\cdot10^{11}$ cm^{-2} in the structural components of upper bainite and hardening martensite.

Such structures as lower bainite and tempered martensite provide a high set of mechanical properties of the metal of welded joints of high-strength steels. These structures are characterized by the absence of extended concentrators of crack formation due to the absence of dislocation clusters – zones of deformation localization, which significantly affect the level of local inner stresses.

TEM examinations allowed establishing the relationship between the parameters of the substructure formed directly with a dislocation structure, namely the level of a localized deformation and inner stress fields, which grow with an increase in dislocation density. It is shown that one of the factors influencing the level of a localized deformation, in addition to the value of dislocation density, is also the substructure of the metal, which causes redistribution of dislocations.

Conclusions

Regularities of influence of technological parameters (cooling rate and welding speed, weld alloying, heat treatment conditions) on structural-phase composition, parameters of grain, subgrain, dislocation structures of welds and heat-affected-zone metal of low-carbon (structural) welded joints of medium-carbon alloy (of special purpose) and high-carbon (wheel) steels and the relationship of the structure with mechanical properties of these joints, level of local inner stresses and a localized deformation formed in different structural components (lower and upper bainite, hardened and tempered martensite, etc.) were determined.

The improvement of experimental-analytical procedure of evaluating the complex of physical and mechanical properties according to specific structural parameters of all elements of the structure was carried out, mathematical data processing was introduced. The correlation between structural parameters and values of strength, fracture toughness, local inner stresses in the metal of welded joints of high-strength steels was established, which allowed classifying the conditions of crack formation relative to the complex of structural components taking into account the density of dislocations and features of the substructure.

It is shown how the microstructure affects the physical and mechanical properties of welded joints of high-strength steels of a wide strength range. The generalization of structural conditions for providing a high level of the complex of mechanical properties and crack resistance of welded joints of high-strength steels made it possible to propose structural criteria and indicate methods to apply them in technologies and promising methods of welding. Based on the structural criteria for the phase composition, dispersion of grain and subgrain structure with a gradientless distribution of dislocation density, scientifically substantiated recommendations for producing high-quality welded joints of high-strength steels for different purposes and a wide range of strength were developed.

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