discharge occurred at tensile stresses up to 150 MPa, to which the elongation of up to 2 % of a specimen of AMg6 corresponds. Its further elongation deteriorates efficiency of treatment which is, as described above, connected with development of deformational strengthening processes, initiated by current discharges [9], which negatively influence the efficiency of EDT process.

CONCLUSIONS

1. EDT has no influence on decrease of values of relative yield strength $\sigma_{0.2}$ and tensile strength σ_t of AMg6 alloy and its welded joints. At EDT of specimens after tension until elasticity limit, the parameters $\sigma_{0.2}$ and σ_t are increased by 15–20 %, and elastic-plastic state is increased, respectively, by 50 and 20 %.

2. The repeated loading of specimens of AMg6 alloy has no substantial influence on efficiency of current impact. At EDT with E = 140 J the relative decrease of level of applied stresses in AMg6 alloy is 20 %, and at E = 800 J it is 65 %.

3. The maximal efficiency of EDT of specimens of AMg6 alloy and its welded joints is observed at σ_{in} = = 150 MPa.

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EFFECT OF ALLOYING OF THE WELDS ON STRUCTURE AND PROPERTIES OF WELDED JOINTS ON STEEL 17Kh2M

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Structural-phase state of metal of the welded joints on high-strength low-carbon steel 17Kh2M ($w_{6/5}$ = 20–23 °C/s) produced by using welding wires of different chemical compositions and structural types (Sv-08G2S, Sv-08Kh20N9G7T, Sv-10KhN2GSMFTYu) was investigated. Analytical estimation of differential contribution of each structural parameter to a change in the set of mechanical properties (strength, ductility) of the HAZ and weld metal, as well as of a character of distribution and localisation of strain, level of local internal stresses, intensity and size of the stress raisers, which are potential sources of cracks forming during the welding process, was carried out on the basis of experimental data.

Keywords: *arc welding, high-strength steel, welded joints, weld and HAZ metal, type of weld alloying, structural-phase parameters, mechanical properties, localised strain, local internal stresses, crack resistance*

High-strength steels with yield stress σ_y = 590 MPa or more are used in the national and foreign practice to fabricate critical welded structures. With the rational utilisation of these steels it is possible to substantially improve technical and economic indices of machines, mechanisms and engineering structures. However, the main problems in welding of high-strength steels are related not only to the requirement to ensure the sufficient strength level, but also to the need to prevent cold cracking of the welded joints. This is determined to a considerable degree by formation of optimal structures in the weld and HAZ metal, which can improve not only strength but also brittle fracture resistance of the welded joints [1–3].

The effect of the structure of metal of the welded joints on their properties is evidenced by the fact that welding of high-strength steels is performed, as a rule, by using consumables that provide welds with the bainitic (B) or bainitic-martensitic (B-M) structures. However, the low- or high-alloyed consumables are used in certain cases to increase cold crack resistance of the welded joints, the resulting welds having the

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Table 1. Chemical composition (wt.%) of steel 17Kh2M and metal of the welds made by using welding wires of different grades

Material	C	Mn	Si	Cr	Ni	Mo	Al	Ti	S	P
Steel 17Kh2M	0.19	0.60	0.20	1.55	0.11	0.30	–	–	0.006	0.014
Welding wire grade:										
Sv-10KhN2GSMFTYu	0.08	1.08	0.30	0.92	1.72	0.43	0.02	–	0.019	0.023
Sv-08G2S	0.08	1.30	0.80	–	–	–	–	–	0.017	0.019
Sv-08Kh20N9G7T	0.08	6.60	0.55	20.70	8.43	–	–	0.40	0.012	0.018

ferritic-pearlitic (F-P) or austenitic-ferritic (A-F) structures. As proved by practice, the processes of structural-phase transitions and their effect on properties of different zones of the welded joints on high-strength steels are little studied as yet. This is attributable to a complicated mechanism of transformation of austenite in the high-strength steel HAZ metal taking place during cooling over a wide range of temperatures [4–6]. Moreover, the phase formation processes and, hence, properties of the welded joints are greatly affected by the composition of the deposited metal.

This study is dedicated to investigation of peculiarities of phase and structural transformations in metal of the high-strength steel welded joints produced by using welding consumables of different compositions, as well as to estimation and prediction of properties of such joints depending on the above factors.

Butt joints on steel 17Kh2M, 20 mm thick, with V-groove (C21 according to GOST 14471–76) and multilayer welds were chosen as the investigation objects. The welded joints were made by mechanised arc welding in a shielding atmosphere of the Ar + + 22 % CO_2 gas mixture by using 1.2 mm diameter solid wires of the Sv-08G2S (weld of the F-P type), Sv-08Kh20N9G7T (weld of the A-F type) and Sv-10KhN2GSMFTYu (weld of the B-M type) grades under the following conditions: I_w = 120–140 A, U_a = 22–24 V, $v_w \approx$ 18 m/h (for welding of the root bead); and I_w = = 160–180 A, U_a = 26–28 V, $v_w \approx$ 13–14 m/h (for making the next weld layers, thus providing cooling of the HAZ metal at a rate of $w_{6/5} \approx$ 20–23 °C/s). Chemical composition of the investigated steel and weld metal of the joints welded by using the above welding consumables is given in Table 1.

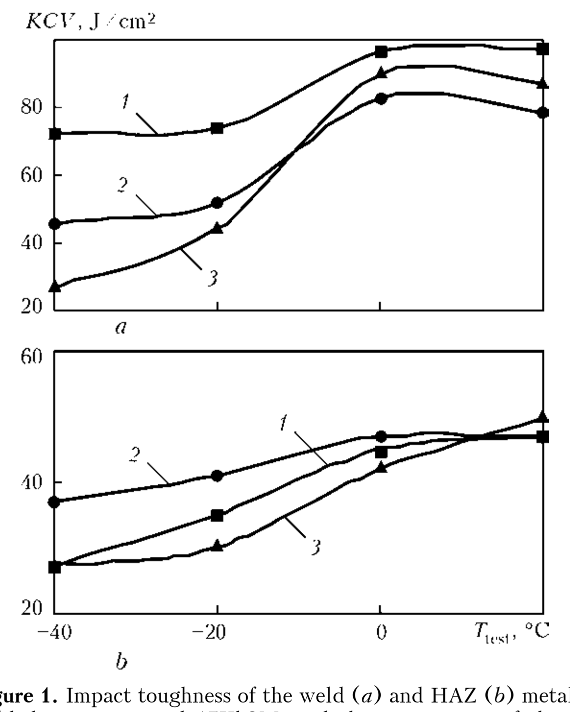

Figure 1. Impact toughness of the weld (*a*) and HAZ (*b*) metal of welded joints on steel 17Kh2M made by using wires of the Sv-08Kh20N9G7T (*1*), Sv-10KhN2GSMFTYu (*2*) and Sv-08G2S (*3*) grades

Specimens for mechanical tensile and impact bend tests (type II according to GOST 1497–84) were cut in the transverse direction relative to the weld axis. An annular groove 2 mm wide and 0.5 mm deep was made in them to localise the place of fracture (weld or HAZ). A notch in the impact specimens (type IX according to GOST 9454–78) was also made along the weld and HAZ axis.

As proved by the results of mechanical tests, welds of the B-M type made by using welding wire of the Sv-10KhN2GSMFTYu grade are characterised by the highest tensile strength value ($\sigma_t \approx$ 950 MPa). The lower values of this property were fixed in the welded joints with welds of the F-P ($\sigma_t \approx$ 860 MPa) and A-F ($\sigma_t \approx$ 750 MPa) types.

Results of impact bend tests of the specimens at test temperature T_{test} from +20 to −40 °C show that metal of all the welds investigated has impact toughness values that meet requirements imposed on steel 17Kh2M ($KCV \geq 27$ J/cm^2) (Figure 1). The values of KCV of the weld metal decrease with decrease of T_{test}. The most pronounced decrease in impact toughness takes place in the weld metal of the F-B type at T_{test} = −40 °C (from KCV^{+20} = 90–116 to KCV^{-40} = = 34–47 J/cm^2). The weld metal of the A-F type is characterised by the highest cold resistance (KCV^{-40} = = 78–83 J/cm^2). The values of impact toughness of such welds vary insignificantly with decrease in the test temperature. The welds of the B-M type have sufficiently high values of cold resistance as well.

Composition of the deposited metal also affects mechanical properties of the HAZ metal of the investigated welded joints. While in the joints with the B-M and F-P type welds they differ just insignificantly ($\sigma_t \approx$ 950–1000 MPa), tensile strength of the HAZ metal of the joints with the A-F type welds decreases to $\sigma_t \approx 820$ MPa. Also, there are differences in cold resistance of the HAZ metal of the welded joints with the welds of different alloying compositions. The joints with the B-M type welds have the highest values of impact toughness at the negative temperature. These values are much lower in the joints with the F-P and A-F type welds. A marked decrease in the impact toughness values of the HAZ metal of such joints begins already at $T_{test} = -20$ °C.

As seen from the results of mechanical tests, properties of the weld and HAZ metal of the welded joints on steel 17Kh2M depend on the composition of the deposited metal. Hence, they are related to peculiarities of the structures forming in them.

Structural-phase and concentration changes, a character of distribution and density of dislocations in the weld and HAZ metal were studied in detail by the integrated investigation method, which comprises optical metallography, analytic scanning electron microscopy (SEM-515 of the «Philips» Company, the Netherlands) and microdiffraction transmission electron microscopy (JEM-200CX of the JEOL Company, Japan). This made it possible to generate experimental information at different structural levels — from macro (grain) to micro (dislocation) level. This approach allows differential estimation of the contribution of individual structural-phase factors and parameters (phase composition, grain D_g and subgrain d_s sizes, dislocation density ρ, size of phase precipitate particles d_p and distance between them λ_p, etc.) to changes in the total (integrated) values of mechanical properties of the weld and HAZ metal, i.e. strength (proof stress $\sigma_{0.2}$ and tensile strength σ_t), brittle fracture resistance K_{IC}, distribution of localised strain ε_l and local internal stresses τ_{in} acting as internal stress raisers, which may be potential sources of fracture of the welded joints under certain conditions.

The following was established as a result of investigations of structural-phase components (pearlite P, ferrite F, upper bainite B_{up}, lower bainite B_{low}, and martensite M), grain size D_g and volume content V_c of these phases forming in the weld metal and in different HAZ regions during the welding process, as well as corresponding changes in microhardness HV.

Weld metal of the welded joints produced by using wire Sv-08G2S under the investigated cooling conditions consisted of coarse-grained (D_g = 50–100 μm) and dramatically graded (ΔD_g — more than 2–3 times) F and P structures with microhardness HV 1920–2100 MPa (Figures 2, *a* and 3) in the presence of the clearly defined orientation of columnar crystalline grains (h_{cr} = 40–100 μm) along the fusion

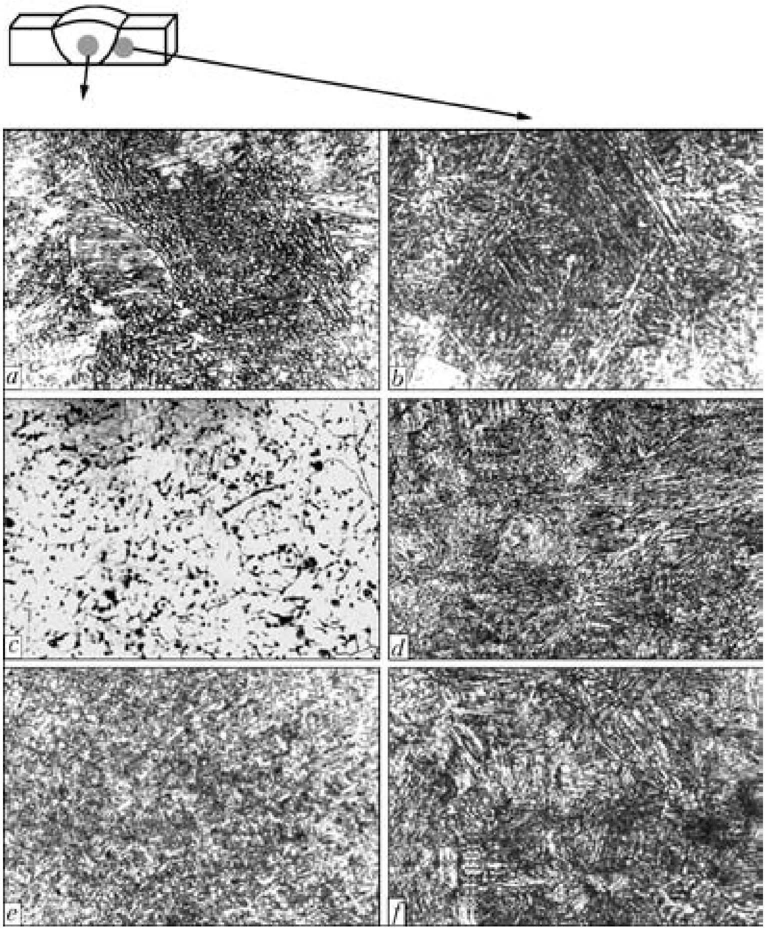

Figure 2. Microstructures (×1000) of metal of the welds (*a*, *c*, *e*) and coarse-grained regions (region I of HAZ) of welded joints on steel 17Kh2M (*b*, *d*, *f*) produced by using welding wires Sv-08G2S (*a*, *b*), Sv-08Kh20N9G7T (*c*, *d*) and Sv-10KhN2GSMFTYu (*e*, *f*) at $w_{6/5}$ = 20 °C/s

Table 2. Average values of structural parameters of welded joints on steel 17Kh2M produced by using welding wires of different grades

Investigated region	Structure	V_c, %	D_g, μm	d_s, μm	λ_p, μm	ρ, cm^{-2}	
						Local	Total
Sv-08G2S							
Weld	F	40	100 μm (h_{cr})	1.7	–	$1\cdot10^9$	$6\cdot10^9$–$2\cdot10^{10}$
	P	60		≤ 1.0	–	$(3–5)\cdot10^{10}$	
Region I of HAZ	F	7	5.5	1.7	–	$2\cdot10^9$	$(5–6)\cdot10^{10}$
	B_{up}	50	77	0.5	0.30	$(1.0–1.3)\cdot10^{11}$	
	B_{low}	43	42	0.45	0.10	$(6–7)\cdot10^{10}$	
Sv-08Kh20N9G7T							
Weld	A-F	100	20	2.0–5.0	–	$(3–4)\cdot(10^9–10^{10})$	$(3–4)\cdot(10^9–10^{10})$
Region I of HAZ	F	5	3	1.8	–	$2\cdot10^9$	$5\cdot10^{10}$
	B_{up}	40	60	0.45	0.27	$(8–9)\cdot10^{10}$	
	B_{low}	55	38	0.4	0.08	$(5–6)\cdot10^{10}$	
Sv-10KhN2GSMFTYu							
Weld	B_{up}	20	30	0.46	0.30	$8\cdot10^{10}$–$1\cdot10^{11}$	$(4–5)\cdot10^{10}$
	B_{low}	30	30	0.3	0.02	$5\cdot10^{10}$–$1\cdot10^{11}$	
	M	50	–	1.0	–	$1\cdot10^{11}$	
Region I of HAZ	F	4	2	1.5	–	$3\cdot10^9$	$(6–7)\cdot10^{10}$
	B_{up}	30	52	0.35	0.10	$(1–3)\cdot10^{11}$	
	B_{low}	45	30	0.2	0.06	$5\cdot10^{10}$–$1.1\cdot10^{11}$	
	M	21	–	0.88	–	$1\cdot10^{11}$	

line on the weld side. HAZ of such joints is also characterised by formation of a considerable volume content of coarse-grained ($D_g \approx 20$–80 μm) B_{up} structures, i.e. $V_{B_{up}} \sim 50$ and 25 %, at a substantially lower volume content of B_{low} (approximately 15 % lower) and presence of ferrite fringes ($V_{f.f} \approx 7$ %) (Figures 2, *b* and 3, and Table 2).

At a similar cooling rate the weld metal of the welded joints made by using wire Sv-08Kh20N9G7T has an equiaxed, more uniform in grain size and two-phase fine-grained ($D_g \approx 20$ μm) A-F structure (Figure 2, *c*) with a volume content of F equal to about 1.3–1.5 %. The following structural changes take place in the HAZ metal of such joints, compared to the welded joints with the F-P type welds. With a general refinement of the structure (by 10–30 %), especially in the coarse-grained and normalised regions, and at a 4–10 % increase in microhardness, there is a change in phase composition of structural components of metal in all the HAZ regions: region I is characterised by increase (1.3 times) in the volume content of B_{low} (approximately to 55 %) and decrease in that of B_{up} (to 40 %), and region II is characterised by increase in the volume content of the ferrite component (to 30 %).

Formation of the M structure takes place in the coarse-grained region of the welded joints on steel 17Kh2M produced by using wire Sv-10KhN2GSMFTYu, compared to the welded joints with the F-P type welds. The volume content of this structure changes comparatively uniformly, approximately from 50 to 20 % (in transition from the weld to HAZ metal). Also, a substantial decrease in the volume content of B_{up}, approximately by 40 %, takes place in this case, the ferrite component being absent (Figure 2, *e*, *f*, and Table 2). In addition, we should note a substantial (1.2–1.5 times) refinement of the structure (B_{up} — approximately to 30–50 μm, and B_{low} — to 20–30 μm).

Analysis of the concentration changes in the investigated welded joints, and first of all of the composition of main chemical elements (chromium, nickel and manganese), showed that the most abrupt gradients of the content of chromium (from 2 to 11 wt.%), nickel (from 3 to 6 wt.%) and manganese (from 0.5 to 4 wt.%) occur near the fusion line in the welded joints produced by using welding wire Sv-08Kh20N9G7T (weld of the A-F type). In the welded joints with the F-P and B-M type welds the gradient of the concentration changes in the welding zone is not in excess of 1.5 %.

Results of transmission electron microscopic examinations of fine structure, which give an idea of the type of the forming structures, variations in density and distribution of dislocations in different structural components (in the bulk of grains, along structural

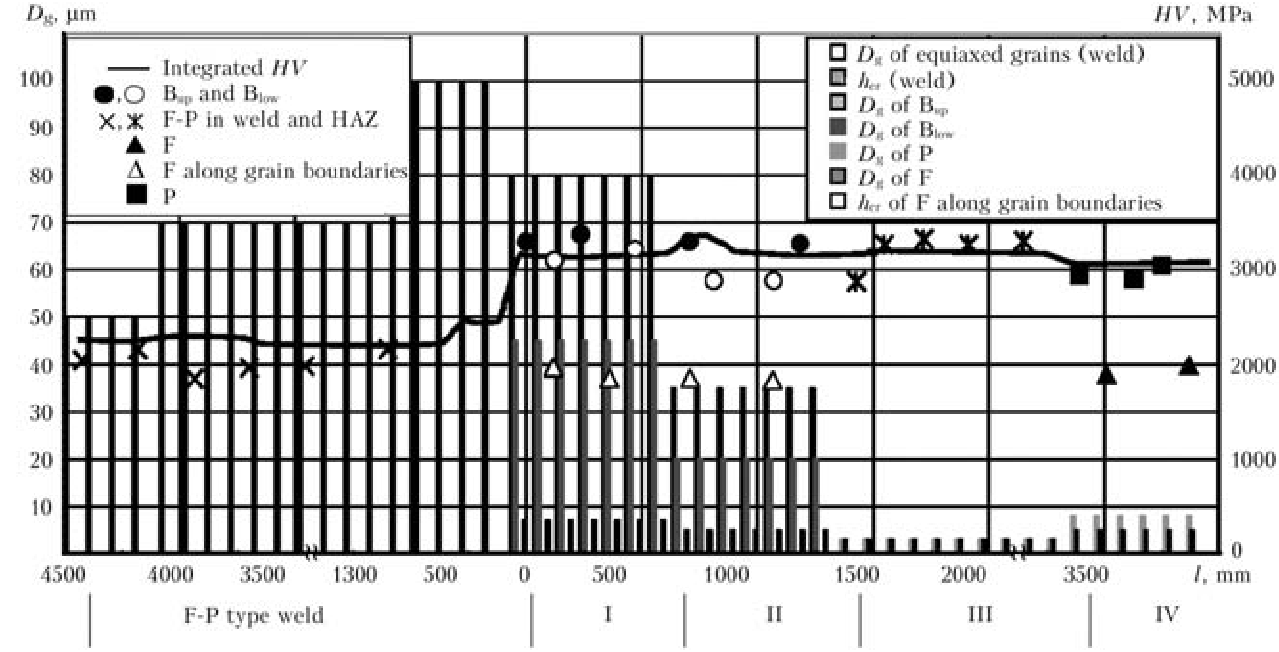

Figure 3. Variation in microhardness HV and grain size of structural-phase components in the weld metal and all HAZ regions of the welded joint on steel 17Kh2M produced by using wire Sv-08G2S: I–IV — HAZ regions: I — overheated (coarse-grained) region; II — refined (normalised) region; III — incompletely refined region; IV — recrystallised region; l — distance from the fusion line

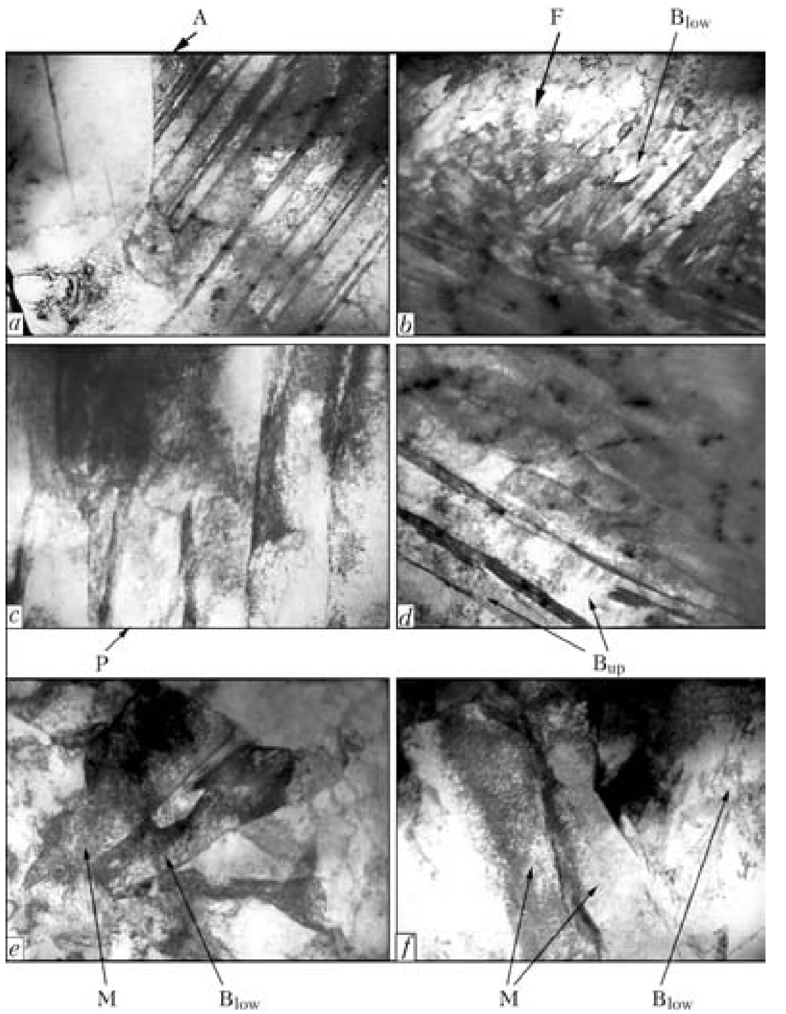

Figure 4. Fine structure of metal of the welds (a, c, e) and coarse-grained regions (region I of HAZ) of welded joints on steel 17Kh2M (b, d, f) produced by using welding wires Sv-08Kh20N9G7T (a, b), Sv-08G2S (c, d) and Sv-10KhN2GSMFTYu (e, f) (a — ×10,000; b, c, e, f — ×15,000; d — ×20,000)

boundaries) showed the following. The most uniform intragranular distribution of dislocations at their low density ($\rho \sim (3–4)\cdot(10^9–10^{10})$ cm^{-2}) is characteristic of the structure of the A-F type weld metal (Figure 4, *a*). With transition from the weld to HAZ the dislocation density increases to some extent both in the internal volumes of B grains ($\rho \sim 5\cdot10^{10}$ cm^{-2}) and along their boundaries, especially in B_{up}, where the values of this indicator amount to $\rho \approx (8–9)\cdot10^{10}$ cm^{-2} (Figure 4, *b*, and Table 2).

Compared to the joints produced by using wire Sv-08Kh20N9G7T (the A-F type weld), the welded joints with the F-P type welds feature some general increase in the dislocation density both in the weld metal (Figure 4, *c*) (1.5–2 times) and in HAZ (1.2 times) (Table 2). Like in the previous case, the structural zones characterised mainly by formation of the dislocation clusters are the extended intergranular boundaries of B_{up}. The dislocation density in such clusters amounts approximately to $(1.0–1.3)\cdot10^{11}$ cm^{-2} (Figure 4, *d*).

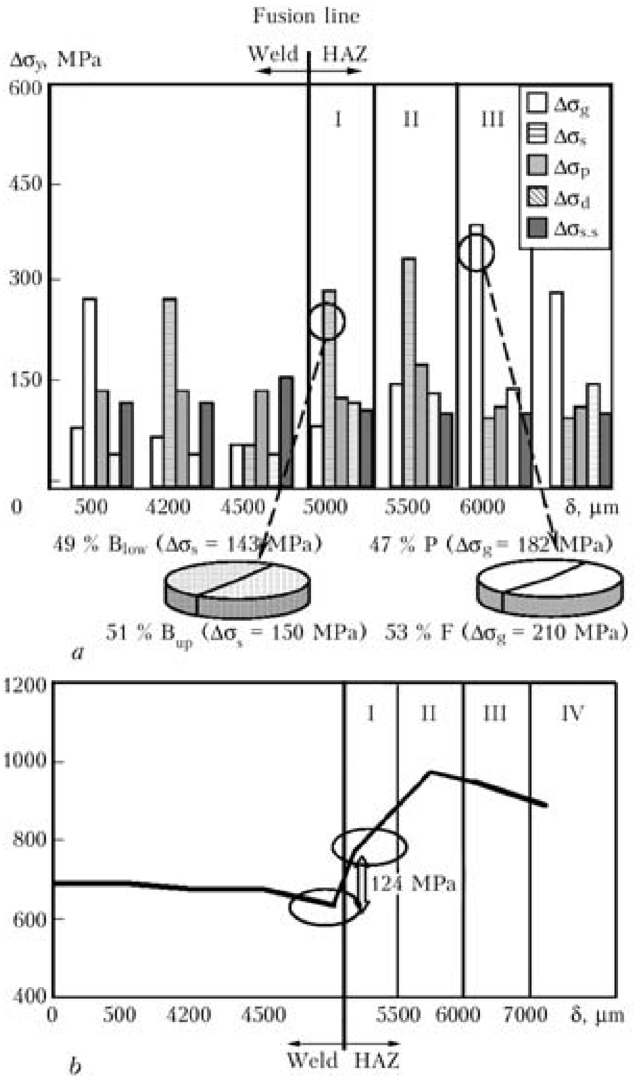

Figure 5. Bar and pie charts (*a*) reflecting differential contribution of individual structural parameters (grain and subgrain size, dislocation density, phase precipitates) to total (integrated) value of σ_y (*b*) in the weld metal and all HAZ regions in welding of steel 17Kh2M by using wire Sv-08G2S: $\Delta\sigma_d$ — dislocation strengthening; $\Delta\sigma_{s.s}$ — strengthening of solid solution by alloying elements; see the text for the rest of the designations

Compared to the welds of the F-P type, the welded joints with the B-M type welds are characterised by even higher values of the intragranular density of dislocations at their comparatively uniform distribution both in the HAZ regions (up to $\rho \sim 7\cdot10^{10}$ cm^{-2}) and in the weld metal ($\rho \sim 5\cdot10^{10}$ cm^{-2}), as well as by increase in the dislocation density along the grain boundaries, i.e. B_{up}, where $\rho \approx 3\cdot10^{11}$ cm^{-2} (Table 2, and Figure 4, *e*, *f*).

Therefore, comparison of the structural state of the weld metal in the investigated welded joints showed that wire Sv-10KhN2GSMFTYu used as a filler metal to produce welds of the B-M type provides the highest increase in the volume content of B_{low} (approximately by 30–35 %) and M (about 20–50 %) in the deposited metal, decrease (1.3–1.7 times) in the content of B_{up}, uniform growth of microhardness in all the HAZ regions, general refinement of structure and substructure, and rise in the density of dislocations with their comparatively uniform distribution. Noteworthy is a fundamental difference in formation of the dislocation clusters in the B_{up} and B_{low} structures (for B_{up} these are extended zones with a rather high dislocation density, and for B_{low} — short dislocation clusters with closed internal substructure).

The experimental data base generated as a result of investigations at all structural levels (from macro to micro) allowed analytical estimations of the most significant mechanical and service properties of the welded joints. For instance, the estimates obtained by using the Archard equation that includes the known Hall–Petch, Orowan and other dependencies [7–16] made it possible to determine the differential contribution of specific structural components (phase composition, alloying, grain and subgrain sizes, dislocation density, size, distribution and volume content of phase precipitates etc.) to a total (integrated) change in such strength characteristic as yield stress [17–21].

It follows from the results of experimental studies and analytical estimations (Figure 5) that in the welded joints produced by using wire Sv-08G2S the total (integrated) value of strengthening, $\Sigma\sigma_{0.2}$, of the weld metal is provided primarily by the carbide phase effect, substructure and increase of the dislocation density. In the welded joints with the A-F type welds their strengthening is related mainly to the growth of solid solution and grain strengthening caused by grain refinement. This is accompanied by decrease in the contribution of the substructural and dislocation components. As to the HAZ metal, strengthening in the overheated region grows (compared to the weld metal) for both types of the joints approximately 1.2–1.5 times, which is related to increase in the content of the bainite component. In addition, strengthening of the HAZ metal in the joints with the A-F type welds is caused by formation of the carbide phases, development of the substructure and growth of the dislocation density, which is associated with formation of the bainite phases in this region (especially B_{low}).

Transition from the weld to HAZ in the welded joints produced by using wire Sv-10KhN2GSMFTYu is characterised by a smoother change in the total level of strengthening, $\Sigma\sigma_{0.2}$, both near the fusion line on the side of the weld and in all the HAZ regions. The highest contribution to strengthening is made by refinement (dispersion) of the substructure ($\Delta\sigma_s \sim 355$ MPa) and carbide phase particles ($\Delta\sigma_p \sim 183$ MPa) in the B_{low} grains.

Therefore, comparison of the strengthening effect of the structures forming in metal of the investigated welds of the F-P → A-F → B-M transition system indicated the presence of the structural factors that are most significant in the level of the effect, i.e. B_{low}.

The strengthening contribution of B_{low} ($\Delta\sigma_{B_{low}}$) due to its external and internal components (sizes of grains $\Delta\sigma_g$ and subgrains $\Delta\sigma_s$, and of carbide phase particles $\Delta\sigma_p$) to the total (integrated) strength values $\Sigma\sigma_{0.2}$ of the welded joints is as follows: $\Delta\sigma_{B_{low}} \approx 287$ MPa for F-P, $\Delta\sigma_{B_{low}} \approx 395$ MPa for A-F, and $\Delta\sigma_{B_{low}} \approx 438$ MPa for B-M. As seen, the contribution of B_{low} grows with transition from the F-P type weld to the A-F type and B-M type welds.

The role of the structural factors also shows up in a change of structural strength of the welded joints with the F-P, A-F and B-M type welds, i.e. in a combination of values of yield stress σ_t and stress intensity factor K_{IC} (Figure 6). The given values of the stress intensity factor were determined from the Krafft dependence [22]: $K_{IC} = (2E\sigma_t\delta_t)^{-1/2}$, where E is the Young modulus, is assumed to be equal to $\Sigma\sigma_{0.2}$, and σ_t is the critical crack opening displacement determined from the data of fractographic analysis of fractures and substructure parameters [18, 20]. It was established that the value of K_{IC} of the weld metal of the welded joints produced by using wire Sv-08Kh20N9G7T was somewhat higher, compared to the F-P and B-M type welds. It was caused by a substantial decrease in grain size, formation of a clearly defined substructure and uniform distribution of dislocations. The lower values of K_{IC} of the F-P and B-M type welds are attributable to a general increase and non-uniform distribution of the dislocation density, as well as to growth of the volume content of structures with extended cementite phase precipitates. Meanwhile, it should be noted that the welded joints with the B-M type welds are characterised by a high level of strength without any substantial decrease in the K_{IC} values (Figure 6), this being indicative of a good

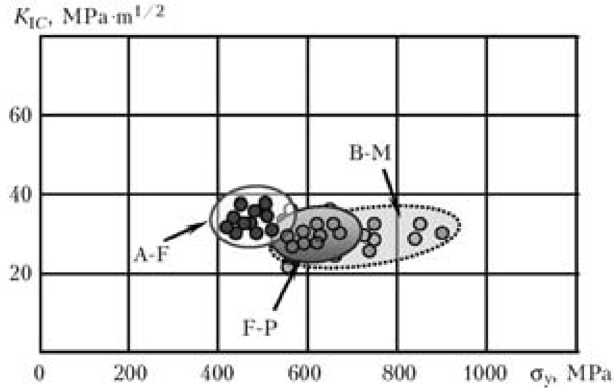

Figure 6. Regions of structural strength of the welded joint on steel 17Kh2M produced by using wires Sv-08G2S (F-P type welds), Sv-08Kh20N9G7T (A-F type welds) and Sv-10KhN2GSMFTYu (B-M type welds)

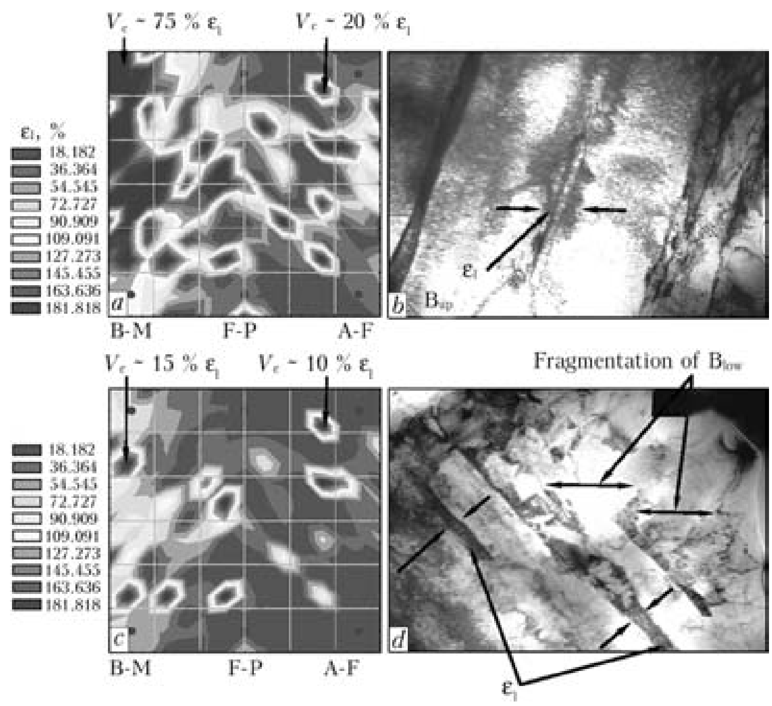

Figure 7. Diagrams (×20,000) of distribution of the zones of localisation of strains in B_{up} (*a*, *b*) and B_{low} (*c*, *d*) of different types of the weld metal

combination of strength and toughness characteristics of the welded joints.

The next step in structural-analytical investigation of the effect on properties of the welded joints by structural parameters was revealing a real picture of interrelation between the structural factors and distribution and intensity of the zones of localisation of strain ε_l and internal stresses τ_{in} in the weld and HAZ metal of the given joints. The required experimental information for analysis of this effect was obtained from examination of fine (dislocation) structure, density and size of structural-phase components in different regions of the joints. Analytical estimations of this type of the clusters were made by using the Conrad and Stroh relationships [23, 24] (respectively, $\varepsilon_l = \alpha_1 \rho b S$ and $\tau_{in} = Gbh\rho / \pi(1 - \nu)$, where $\alpha_1 = 1.4$ is the coefficient that relates tensile strain to shear strain; ρ is the dislocation density; b is the Burgers vector; S is the average distance of movement of dislocations during loading, which practically corresponds to the substructure parameters; G is the shear modulus; $h = 2 \cdot 10^{-5}$ cm is the foil thickness; and ν is the Poisson's ratio).

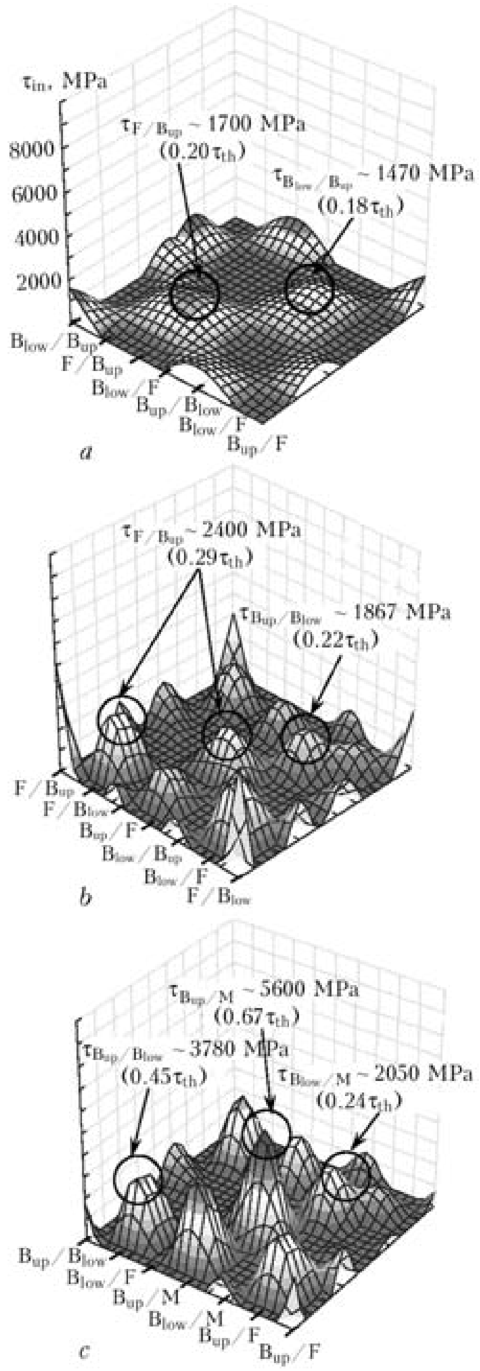

Figure 8. Calculated values of internal stresses τ_{in} and theoretical strength τ_{th} in different structural zones of their localisation (B_{up}, B_{low}, F, M and their interfaces) (region I of HAZ) in welded joints on steel 17Kh2M produced by using wires Sv-08Kh20N9G7T (A-F type welds) (*a*), Sv-08G2S (F-P type welds) (*b*) and Sv-10KhN2GSMFTYu (B-M type welds) (*c*)

The diagrams of distribution of strain localisation zones for the most significant structures of B_{up} and B_{low} in the investigated welded joints show that the most intensive localisation field of ε_l (V_c ~ 75 %) forms in the B_{up} structures of the HAZ metal of the welded joints with the B-M type welds (Figure 7, *a*, *b*), whereas the most uniform field (in intensity and distribution area) is characteristic of the zones of formation of B_{low} (Figure 7, *c*, *d*).

Results of comparison of the estimated τ_{in} values with the value of theoretical strength τ_{th} of the material (Figure 8) showed the following. A lower general level of local internal stresses distributed in the overheated region of the HAZ metal forms in the welded joints produced by using wire Sv-08Kh20N9G7T (τ_{in} = 1500–1700 MPa), which is approximately $(0.18–0.20)\tau_{th}$ (Figure 8, *a*). Increase in the τ_{in} values approximately 1.3–1.4 times is characteristic of the joints with the F-P type welds (Figure 8, *b*). The highest τ_{in} values (about 3800–5600 MPa) corresponding to $(0.45–0.67)\tau_{th}$, which are relatively uniformly distributed in metal of the corresponding HAZ region, are characteristic of the B-M type welds (Figure 8, *c*).

The following was established concerning the character of distribution of τ_{in} in different types of the structures. The longest (about up to 8–10 μm long) and most intensive dislocation clusters, i.e. internal stress raisers (τ_{in} ~ 5600 MPa) form in the B_{up} structures (along the intergranular cementite layers), which are potential sources of brittle fracture. At the same time, uniform distribution of the local dislocation clusters, decrease in their size and closed character in the bulk of grains correspond to B_{low}. In formation of this type of the structures this leads to wider possibilities for occurrence of plastic relaxation of stresses under conditions of the growing external loads due to connection to conventional (dislocation) and rotational mechanisms of their relaxation. This should be taken into account in development of the technological process for welding of high-strength steels, which must promote formation of primarily the B_{low} structures in the weld and HAZ metal, this being particularly important for welded structures operating under low-temperature conditions.

CONCLUSIONS

1. Integrated investigations at all structural levels of the processes of formation of welded joints under actual welding conditions established the effect of specific structural-phase changes during austenitic transformations on strength, ductility and character of localisation of strains and internal stresses, i.e. the factors that influence crack resistance of the welded joints.

2. It was determined that transition from the F-P type welds to the A-F type welds and then to the B-M type ones in the welded joints is accompanied by increase in the content of the B_{low} structures, refinement of the structure and substructure at the absence of abrupt gradients in grain size, as well as a more uniform distribution of the dislocation density in the bulk of grains.

3. It was proved by analytical estimation of differential contribution of the specific structural-phase parameters to the total (integrated) level of strength that increase in strength $\sigma_{0.2}$ of the joints with the B-M type welds is provided by the highest contribution to strengthening of the structures of B_{low} by its components (substructure and carbide phases). Lower values of the strength level in the joints with the A-F and F-P type welds are related to a considerable degree to formation of the coarse-grained and size-graded structures, as well as to a higher volume content of B_{up}.

4. The uniform distribution of local internal stresses τ_{in} and zones of localisation of strains ε_l with decrease in values of these parameters (approximately to $(0.18–0.20)\tau_{th}$) occurs in the welded joints with the A-F type welds. Increase in the τ_{in} value to $(0.22–0.67)\tau_{th}$ is characteristic of the welded joints with the F-P and B-M type welds.

5. The longest and most intensive dislocation clusters, i.e. internal stress raisers, which are potential sources of brittle fracture, form in the B_{up} structures. The uniform distribution of the local dislocation clusters, which is characteristic of the B_{low} structures, decrease in their size and closed character must promote realisation of plastic mechanisms of relaxation of internal stresses.

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