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EFFECT OF METAL STRUCTURE ON SERVICE PROPERTIES OF HIGH-STRENGTH STEEL WELDED JOINTS PRODUCED USING DIFFERENT METHODS OF WELDING*

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Evaluations of effect of forming structures and phase constituents on change of the most significant mechanical properties of welded joints were carried out based on investigation of peculiarities of formation of structural parameters in welded joints of high-strength steel, produced by different methods of fusion welding (laser, arc and hybrid laser-arc). A role of structural factors (alloying, phase constituents, grain, subgrain structure, distribution and density of dislocations, phase precipitations, their size and nature of distribution) was shown in providing the optimum properties of the welded joints and their service reliability. It is shown that the most significant structural-phase parameters and factors, providing under operation conditions, the necessary complex of properties of welded joints, namely strength (σ_y), fracture toughness (K_{1C}) and crack resistance (τ_{in}), are fineness of grain and subgrain structures; dispersion of phase precipitations at their uniform distribution; absence of extended dislocation accumulations — potential concentrators of internal stresses (zone of nucleation and propagation of cracks). 23 Ref., 6 Figures.

Keywords: *laser welding, arc welding, hybrid laser-arc welding, high-strength steel, welded joints, structure, phase composition, mechanical properties, fracture toughness, crack resistance*

High-strength steels with 700 MPa yield point and more are widely used in the world practice in manufacture of metal structures of heavy-loaded machines and mechanisms. As a rule, welded joints, produced of such steels, have good resistance to static and dynamic loadings at positive as well as negative temperatures [1–5].

Manufacture of welded structures of high-strength steels is mostly carried out using mechanized or automatic welding in shielding gases, mainly it is a mixture based on argon with addition of 18–22 % of carbon dioxide. Rarely, automatic submerged-arc welding is used for these purposes. Manual arc welding with coated electrodes is still widely used in repair and assembly of structures from high-strength steels.

As a rule, solid and flux-cored wires of small diameter (1.2–1.4 mm) are used for mechanized gas-shielded welding as well as limitations of welding modes (I_w = 160–220 A, U_a = 21–28 V; v_w = 12–25 m/h). Under such welding conditions a cooling rate of HAZ metal of welded joints ($w_{6/5}$) in a temperature interval of the smallest austenite stability (for high-strength steels this makes 600–500 °C) can vary in a wide limits from 10 to 40 ° C/s. This allows providing required strength, ductility and impact toughness to the weld metal of high-strength steel welded joints including at negative temperatures.

The main disadvantage of indicate welding process lies in its low efficiency. Therefore, in recent time, it is an active search of new, more efficient processes applicable to high-strength steel welding. Laser and hybrid laser-arc welding can be referred to such processes. In comparison with arc welding these processes allow rising welding efficiency several times [6–8]. It is achieved due to increase of power of laser radiation source as well as rise of rate of its movement along the joint to 50–110 m/h.

However, as it is known [9–11], change of the technological modes of welding can result in significant changes of structure of weld metal and HAZ of welded joints and, respectively, to variation of their mechanical properties. These problems are poorly studied in scope of high-strength steels.

In this connection, the aim of presented work was investigation of effect of structure and phase com-

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A.V. Siora and E.V. Polovetsky participated in the work.

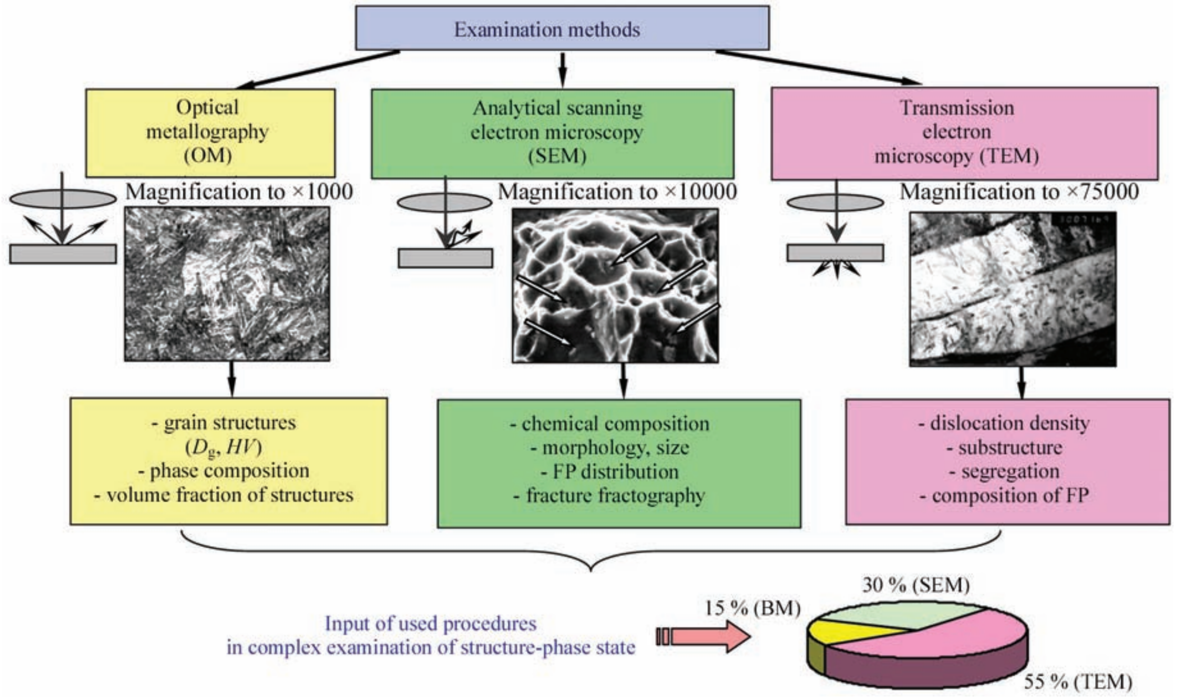

Figure 1. Block diagram of complex methods of examination

position of metal in a welding zone of high-strength steel joints produced by different welding methods (arc, hybrid, laser-arc, laser) on change of the most significant service properties of the welded joints.

To solve stated problems the investigations were carried out at all structural levels (using the methods of optical metallography, scanning and transmission electron microscopy) as for change of structure-phase state as well as dislocation density in different zones of welded joints, at different welding modes. Based on performed experimental investigations it was an analytical estimation of a role of structure-phase changes in the joint metal in formation of the most significant service properties of the welded joints, namely strength (σ_y), fracture toughness (K_{1C}) as well as crack resistance, caused by level of local internal stresses (τ_{in}) taking into account distribution of dislocation density (ρ).

Materials and investigation procedures. The investigations were carried out on the samples of 14KhGN2MDAFB high-strength steel (wt.% 0.183 C; 1.19 Cr; 0.98 Mn; 2.07 Ni; 0.22 Mo; 0.08 V; 0.33 Si; not more than 0.018 P and 0.005 S) of up to 10 mm thickness. In the case of arc and hybrid laser-arc welding Sv-10KhN2GSMFTYu solid section wire (wt.% ≤ 0.1 C; 0.7 Cr; 0.4 Mn; 0.22 Mo; 0.15 V; 0.24 Si; 0.007 S) was used. Laser welding was carried out without filler materials. The welded joints were produced at the following welding modes.

Arc welding. Welding was carried out in a rigid circuit at the next welding rates: 1st mode — v_w = 18 m/h; 2nd mode — 30 m/h; 3rd mode — 40 m/h; 4th mode — 50 m/h. Cooling rate of HAZ metal in 600–500 °C temperature interval made, respectively: $w_{6/5} \approx$ 10–12; 19–22; 25–28; 38 °C/s; I_w = 220–240 A; U_a = 30–32 V.

Hybrid laser-arc welding: 1st mode — v_w = 72 m/h, $I_w \sim$ 125 A, $U_a \sim$ 23 V; 2nd mode — v_w = 90 m/h, $I_w \sim$ ~ 150 A, $U_a \sim$ 25 V; 3rd mode — v_w = 110 m/h, $I_w \sim$ ~ 200 A, $U_a \sim$ 26 V. Given modes provide cooling of HAZ metal in 600–500 °C temperature interval with $w_{6/5} \approx$ 58–62 °C/s rate. Nd:YAG laser DY 044 (Rofin

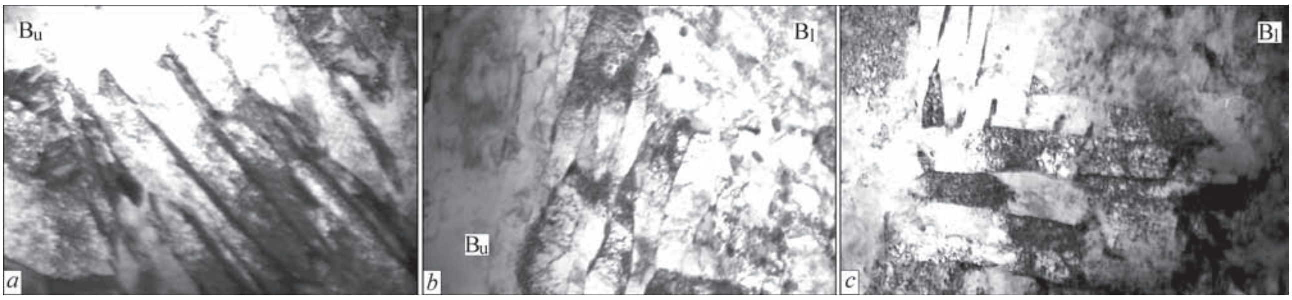

Figure 2. Fine structure (×30000) of weld metal of joints under conditions of different welding modes: *a* — arc; *b* — hybrid laser-arc; *c* — laser

Synar, Germany) of up to 4.4 kW power was used as a laser radiation source and shielding gas (Ar + CO_2 mixture with 15–20 l/min consumption).

Laser welding. Welded joints were received under conditions of different welding rates, i.e. 1st mode — v_w = 18 m/h; 2nd mode — v_w = 30 m/h; 3rd mode — v_w = 50 m/h and cooling rates of HAZ metal: $w_{6/5} \approx 28$; 50; 103 °C/s, respectively.

Methods of structure examinations. The examinations of structure-phase and concentration changes of chemical elements, nature of distribution and density of defects of crystalline lattice in weld metal and HAZ of the welded joints were studied using a complex of experimental methods of modern physical metallurgy, including optical metallography (microscopes «Versamet-2» and «Neophot-32»), analytical scanning electron microscopy (SEM-515, PHILIPS Company, Netherlands) and transmission electron microscopy (JEM-200CX, JEOL Company, Japan) (Figure 1). Hardness was measured on microhardness gage of LECO Company at 0.1 kg loading.

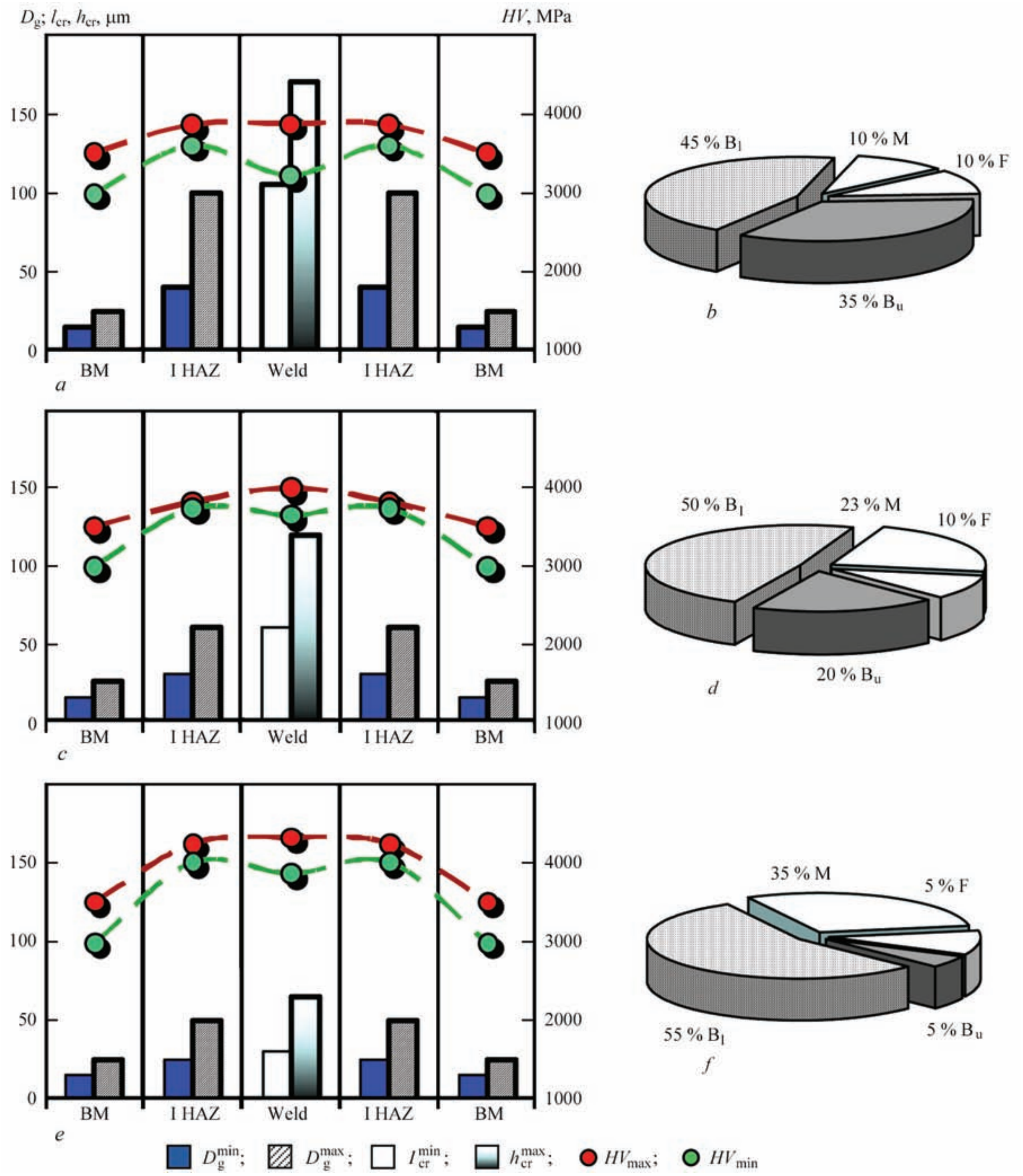

Figure 3. Change of structure parameters of forming phase constituents (B_l, B_u, F, M) at different modes of welding (*a*, *b* — arc, v_w = = 40 m/h; *c*, *d* — hybrid laser-arc, v_w = 72 m/h; *e*, *f* — laser, v_w = 50 m/h): *a*, *c*, *e* — change of grain size (D_g), width (h_{cr}) and length (l_{cr}) of crystallines, microhardness (*HV*) in base metal (BM), in weld metal (WELD), areas of coarse grain (I HAZ); *b*, *d*, *f* — volume fraction (%) of phase constituents

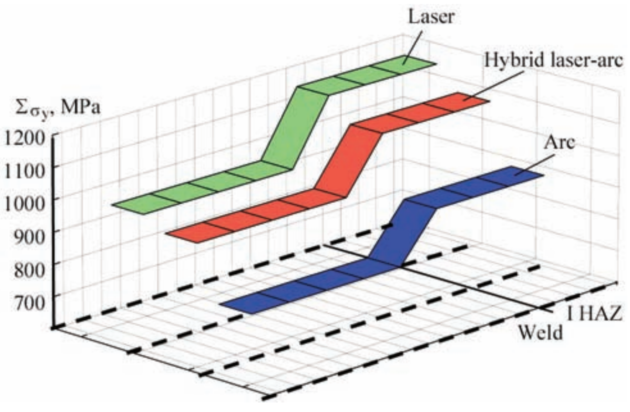

Figure 4. Change of average calculation value $\Sigma\sigma_y$ on zones of welded joints (I HAZ) (weld, I HAZ) of 14KhGN2MDAFB steel at different welding modes

Results of examinations. Changes of structure-phase composition in a welded material zone (steel 14KhGN2MDAFB) depending on welding modes are presented in Figures 2 and 3. Thus, in the case of arc welding (v_w = 18–50 m/h) formation of a structural state of the following type is observed in the weld metal, i.e. up to 45–65 % of upper bainite (B_u); 5–10 % of martensite (M); 10–20 % of ferrite (F) and 10–35 % of lower bainite (B_l). At transfer to overheating area (I HAZ) the next changes of structure types and their volume fraction are observed, namely B_u 20–45 %; M 15–20 %; F 5 % and B_l 30–45 % with typical structure of base metal of bainite-ferrite type. At that, in the case of v_w = 18 m/h the extended dislocation accumulations up to $\rho = (1–2)\cdot10^{11}$cm^{-2} are formed in the weld metal along grain boundaries, mainly on B_u boundaries. It creates a high gradient of dislocation density (Figure 2, *a*) in such elements of the structure. Such structural changes can result in nonuniform level of mechanical properties along the welding zone and reduction of crack resistance of the welded joints.

Thus, the most significant (from point of view of crack resistance decrease) structural-phase changes (coarse grain gradient structure of mainly B_u) are typical for the welded joints produced using arc welding modes at v_w = 18 m/h.

The examinations of structure and phase composition of welded joints of 14KhGN2MDAFB steel in hybrid laser-arc welding showed that at transfer from v_w = 72 to 110 m/h phase composition of weld metal and HAZ overheating area is preserved the same (bainite-martensite), however, there is a noticeable reduction of B_l volume fraction (to 10–20 %). Transfer to v_w = 110 m/h promotes increase of the integral value of dislocation density to $\rho = 1.5\cdot10^{11}$ cm^{-2} and formation of mainly B_u structure.

The most uniform distribution of dislocation density ($\rho = (4–6)\cdot10^{10}$ cm^{-2}) is typical for structures of B_l at v_w = 72 m/h (Figure 2, *b*; Figure 3, *c*, *d*).

In the case of laser welding the examinations showed that increase of welding rate from v_w = 18 to 50 m/h causes change of phase composition of the weld metal from bainite-ferrite to bainite-martensite (Figure 3, *e*, *f*). At the same time, it should be emphasized that there is formation of mainly fine grain equiaxial B_l structure under conditions of uniform redistribution of volumetric dislocation density (ρ = = $(8–9)\cdot10^{10}$ cm^{-2}), Figure 2, *b*.

In such a way, the examinations showed change of a relationship of forming in the welding zones phase constituents (B_l, B_u, M), their parameters, volume fraction as well as density and distribution of dislocations under conditions of variation of welding modes (from arc to hybrid and laser). Thus, under conditions of arc welding there is mainly formation of B_u structure at total increase of sizes of grain and subgrain structures with nonuniform distribution of dislocation density. Transfer to modes of hybrid, laser-arc and laser welding promotes mainly formation of B_l structures at significant refinement of grain

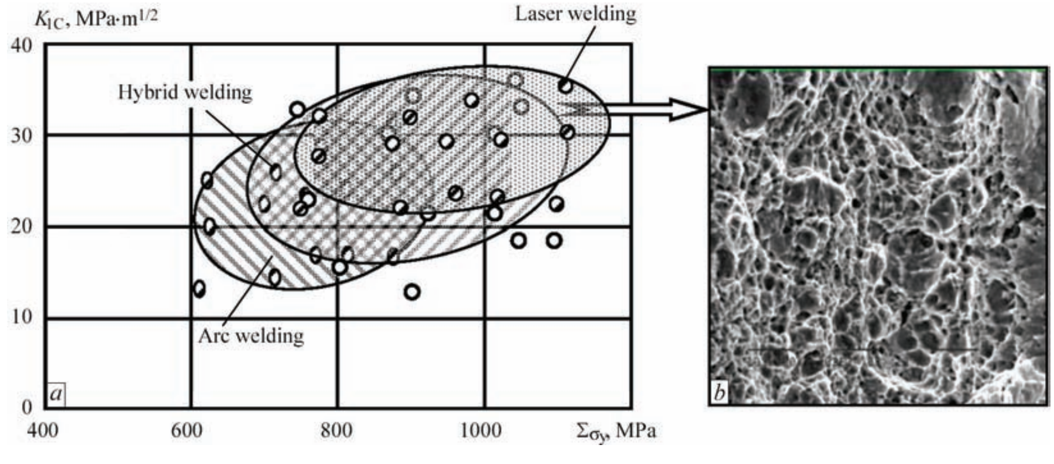

Figure 5. Change of calculation values of strength $\Sigma\sigma_y$ and toughness K_{1C}, (*a*) of metal of welds in arc, hybrid laser-arc, laser welding and fractogram (*b*) of tough fracture of welded joint, produced by laser welding (×2020)

and subgrain with uniform distribution of volume and grain-boundary dislocation density.

Analytical estimations of welded joint service properties. Following the examination of structure-phase changes at different modes of welding the analytical estimations of the most significant service properties of welded joints, namely indices of strength, toughness and crack resistance [12–18] were carried out.

The analytical estimations of strengthening $\Sigma\sigma_y$ were carried out according to known dependencies of Hall–Petch, Orowan, etc. [14–19]: $\Sigma\sigma_y = \Delta\sigma_0 + \Delta\sigma_{s.s} + \Delta\sigma_g + \Delta\sigma_s + \Delta\sigma_d + \Delta\sigma_{d.s}$, where σ_0 is the resistance of type of metal lattice to movement of free dislocations (stress of lattice friction or Peierls–Nabarro stress); $\sigma_{s.s}$ is the strengthening of solid solution by alloying elements (Mott–Nabarro dependence); σ_g, σ_s is the strengthening due to change of grain and subgrain value (Hall–Petch dependence); σ_d is the dislocation strengthening, caused by interdislocation interaction on theory of J. Taylor, A. Zager, N. Mott and G. Hirsch; $\sigma_{d.s}$ is the dispersion strengthening due to dispersion phase constituents by Orowan.

Calculation values of fracture toughness indices K_{1C} were estimated on Krafft dependence [20] K_{1C} =

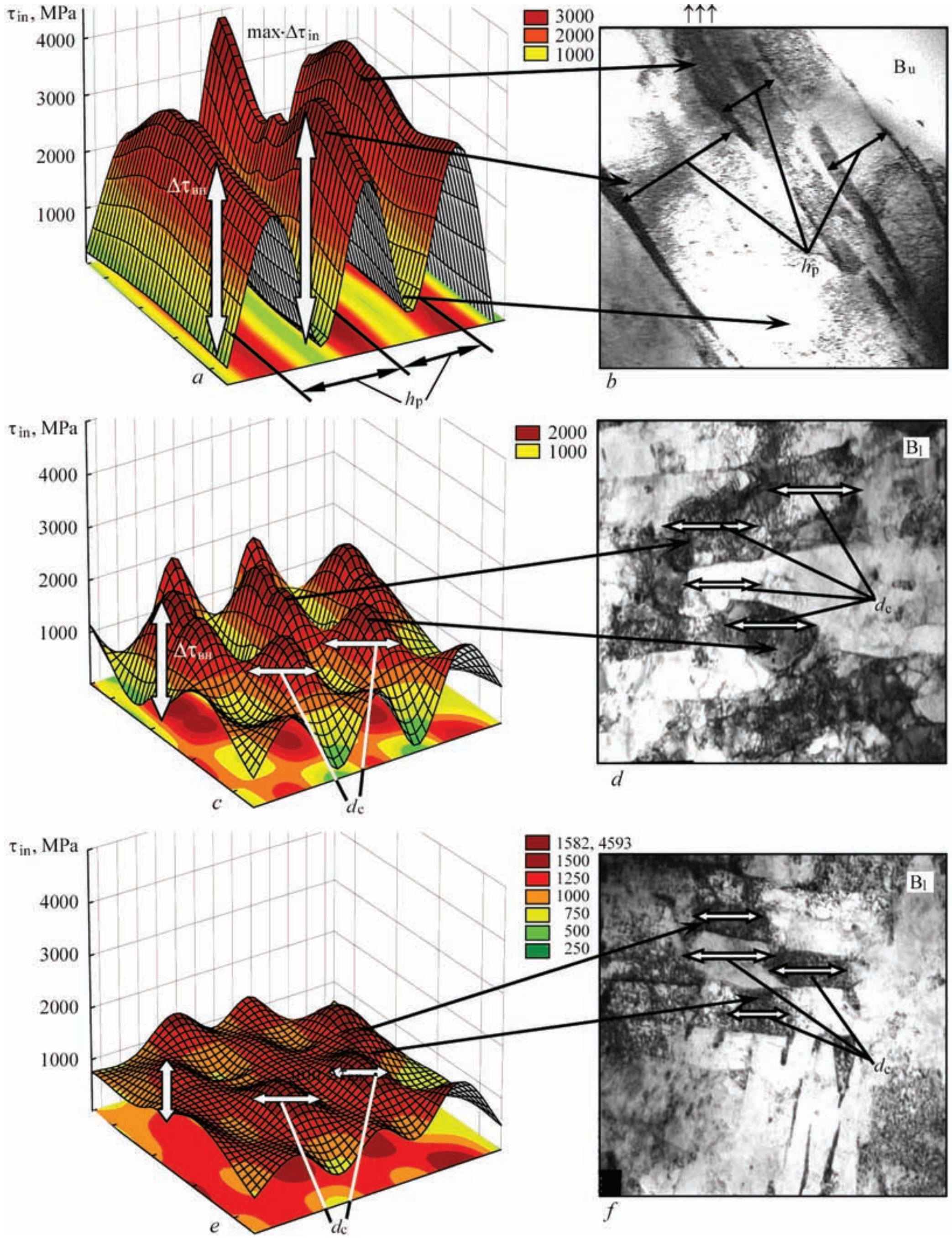

Figure 6. Distribution of local internal stresses (τ_{in}) in metal of welded joints in structural zones: *a*, *b* — B_u in arc welding; *c*, *d* — B_l in hybrid laser-arc; *e*, *f* — B_l in laser welding (*b*, *d*, *f*, ×30000)

= $(2E\sigma_{d.s}\delta_c)^{1/2}$, where E is the Young's modulus; σ_y is the calculation value of strengthening; δ_c is the value of critical opening of crack (according to data of substructure parameters).

Following the analysis of approaches to mechanisms of crack nucleation and material fracture the estimation based on dislocation theory of crystalline solids was selected taking into account nature of dislocation structure and its distribution (dislocation accumulations or uniform distribution of dislocations) [21–23]. A field of internal stresses, developed by dislocation structure (dislocation density) is determined by $\tau_{in} = Gbh\rho/[\pi(1 - v)]$ dependence, where G is the shear modulus; b is the Burgers vector; h is the foil thickness; v is the Poisson's ratio; ρ is the dislocation density [22].

The next was determined as a result of carried estimations. Under conditions of arc welding (v_w = = 40 m/h) the calculation value of $\Sigma\sigma_y$ = 741–890 MPa (Figure 4) in the weld metal and HAZ, respectively. At that fracture toughness index K_{1C} makes around 12–35 MPa·m$^{1/2}$ (Figure 5). Under conditions of modes of hybrid laser-arc (v_w = 72 m/h) and laser welding (v_w = 50 m/h) $\Sigma\sigma_y$ = 850–1080 MPa and $\Sigma\sigma_y$ = 900–1120 MPa, respectively, at increase (by 10–20 %) of level of fracture toughness (Figure 5). The latter is caused by preferable formation of B$_l$ structure at uniform distribution of dislocation density ρ and absence of areas of brittle cleavage on the fracture surface of welded joints (Figure 5, *b*).

The calculation estimations of local internal stresses τ_{in}, given on diagrams of Figure 6, show the following.

The extended zones with maximum values of τ_{in} (1900–3700 MPa) are formed under conditions of arc welding (18 m/h) along grain boundaries of B$_u$ in the places of extended dislocation accumulations (ρ = = (1–2)·10^{11} cm^{-2}), Figure 6, *a*, *b*. This results in nucleation of microcracks in these zones and decrease of crack resistance of welded joints. Reduction of τ_{in} is typical for welded joints produced on hybrid welding modes τ_{in} = 1470–1867 MPa, ρ = 8·10^{10}–1·10^{11} cm^{-2} (Figure 6, *c*, *d*) at v_w = 72 m/h and particularly on modes of laser welding τ_{in} = 1470–1663 MPa, ρ = = (8–9)·10^{10} см$^{-2}$ (Figure 6, *e*, *f*), that promotes formation in a welding zone of fine grain and fragmented B$_l$ structures in combination with uniform distribution of dropping dislocation density.

As a result it is determined that the optimum properties of strength, toughness and crack resistance in high-strength steel welded joints are provided under conditions of laser welding (v_w = 50 m/h) that is caused by formation of more dispersed structures, i.e. B$_l$, fine grain tempered M at absence of extended dislocation accumulations, namely stress concentrators of local internal stresses $\tau_{in.}$

Conclusions

1. Investigations were carried out on structure and service properties of welded joints of 14KhGN2MDAFB high-strength steel depending on used modes of welding (arc, hybrid laser-arc and laser).

2. It is shown that the following transformations of structure are observed under different conditions of welding of 14KhGN2MDAFB steel, namely change of relationship of phase constituents (B$_l$, B$_u$, M) forming in the welding zones as well as their parameters and volume fraction. B$_u$ structures are mainly formed under conditions of arc welding at general increase of size of grain and subgrain structures with their nonuniform distribution and gradient dislocation density.

3. Transfer to modes of hybrid laser-arc and laser welding promotes formation of B$_l$ structures with sharp refinement of grain and subgrain structure at uniform distribution of dislocation density.

4. Analysis of interaction: welding modes → structure → properties indicates significant increase of service properties (strength, fracture toughness, crack resistance) of welded joints of 14KhGN2MDAFB high-strength steel at transfer to laser welding modes, that is related with prevailing effect of fine granulation of forming B$_l$ structures, absence of dense extended dislocation accumulations with preferably uniform distribution of dislocations in the welding zone.

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