EFFECT OF STRUCTURAL FACTORS ON MECHANICAL PROPERTIES AND CRACK RESISTANCE OF WELDED JOINTS OF METALS, ALLOYS AND COMPOSITE MATERIALS

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Investigated are structure and phase composition of weld metals as well as HAZ of welded joints (of carbon, low-alloy structural and cold-resistant steel, nickel and aluminum alloy and others) in fusion welding and reconstruction repair surfacing using different welding consumables (electrodes, fluxes and wires). Analytical estimations of role of forming structural parameters in change of complex of mechanical properties, as well as nature of distribution and localizing of deformations, level of local internal stresses, intensity and extension of stress concentrators, being potential sources of crack formation generated in welding, were carried out based on experimental data, received on different structural levels (from grain to dislocation ones). The results of carried investigations were used for correction of technological processes of welding that allowed providing high complex of mechanical properties and crack resistance of welded joints. 12 Ref., 7 Figures.

Keywords: *arc welding, structural steels, welded joints, structural factors, mechanical properties, crack resistance*

Metal structures and mechanisms of different type used in present time should correspond the main requirements for safety under service conditions. It in particular concerns welded joints of these metals. At that, the most critical criteria characterizing, as a rule, joint safety are yield strength, low brittle transition temperature, crack resistance and good weldability of used metals and alloys. It is a well-known fact that structure and phase composition of these materials play significant, and sometimes vital, role in providing of necessary properties of all types of materials. Therefore, the first «startup» problem is examinations for detection of the most complete scope of structural factors, forming under different conditions of technological treatment (grain, subgrain, dislocation structures and phase composition etc.). And the second problem, being a guiding line for the production engineers in development of optimum technological modes, is investigation of technology ↔ structure ↔ properties relationship, including the structures providing for the maximum necessary service requirements.

This work considers structural factors, which determine properties of the joints, produced by fusion welding [1–9], from such materials as high-strength low-alloy, austenite stainless steels as well as aluminum alloys etc. The factors of following types are the subject of examination, namely non-metallic inclusions (NMI); reinforcement (strengthening) phases; phase composition, depending on alloying (pearlite, ferrite, bainite, martensite and others), and considering structural parameters, such as size of grain and subgrain, dislocation density etc.

The next processes are also considered by analysis of technology ↔ structure ↔ properties relationship. They are peculiarities of deformation localizing and its distribution; structural conditions of formation of local and internal stresses, their changes under thermal-deformation conditions of welding and further internal loading; nature and mechanisms of local internal stress relaxation as well as role of structure and phase composition of metal in processes of realizing of different mechanisms of relaxation of these stresses (due to plastic mechanisms or crack formation). Some examples of such experimental and analytical approaches to estimations are presented in this work.

Effect of NMI on weld properties (strength, impact toughness, cold resistance), formation of

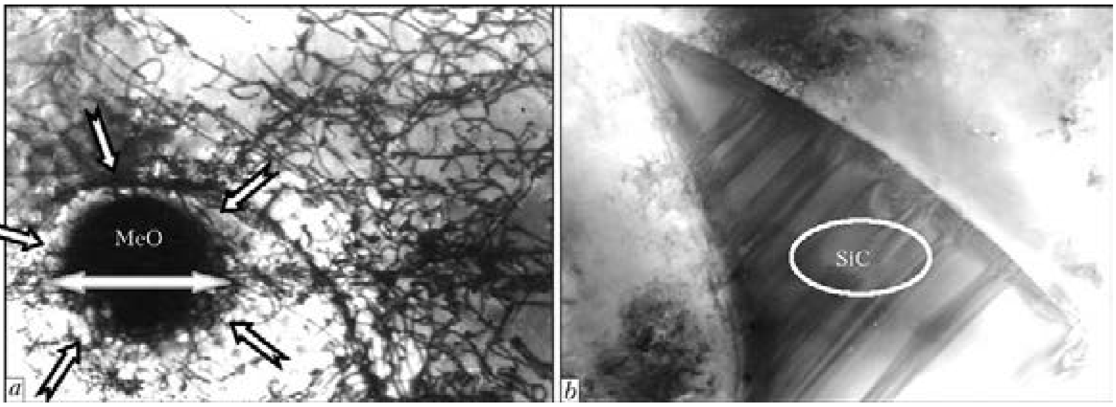

Figure 1. Nature of dislocation configurations ($\tau_{l.in}$ concentrators) in zone of NMI distribution in welded joints, namely oxide phases (*a* — ×10,000), and rise of local stresses along Al/SiC interface and in internal volumes of SiC-phases (*b* — ×20,000)

lamellar cracks etc. were investigated on the welded joints of series of steels. They are the joints of carbon, low-alloy structural and cold-resistant steels [4] produced in gas-shielded submerged arc welding using different coated electrodes (rutile and ilmenite type) [5], submerged arc welding with zirconium [6] and joints with stable austenite welds depending on flux type (basic, acid) [7].

It was shown that formation of specific dislocation configurations of different density and, respectively, various on intensity internal stress fields takes place in weld metal depending on NMI size and their distribution. The fields with high dislocation density are observed in the case of formation of fine-disperse NMI in zone of their accumulation, but at dense distribution in the weld metal. This means formation of the zones with high level of the local internal stresses $\tau_{l.in}$ in area of disperse NMI accumulation. NMI chains distributions are in particular unfavorable (even of disperse size d_p ~ 0.2–0.4 μm) and promote formation of directed dislocation accumulations — $\tau_{l.in}$ concentrators comparable with values of theoretical strength $\tau_{l.in} \sim \tau_{theor}$. At the same time, NMI of larger size (d_p ~ 1.5–1.7 μm), at uniform distribution in grain internal volumes (Figure 1, *a*), do not promote formation of any significant on value local internal stresses in the weld metal and, respectively, have no essential effect on crack resistance of the welded joint metal.

The results of carried investigations and analytical estimations allowed determining the reasonable levels of sufficient weld metal deoxidation, providing not only general reduction of NMI volume fraction, but also more optimum their distribution, and grounding of choice of welding wire compositions [5] as well as application of basic type fluxes for optimizing of welding of carbon, low-alloy structural and stainless steels by stable austenite welds [7].

Investigations on different structural levels showed that *reinforcing and carbide phases* can, depending on their size, be a reason and source of joint fracture with their strengthening effect in welded joint metal. Thus, the maximum strength characteristics of the joints in case of welding of aluminum alloys, reinforced by silicon carbide particles SiC [8], are provided at SiC particle size of around 0.6–0.8 μm. Increase of size approximately to 2 μm resulted in rise of elastic $\tau_{l.in}$ stresses along aluminum matrix/SiC interface, that is verified by change of contrast in this area (Figure 1, *b*) during transmission electron microscope examination. Rising of size of reinforcing phases (welding of aluminum alloys [8]) and carbides (welding of nickel alloys [1]) provokes an avalanche-like increase of dislocation density in the phase internal volumes, along the interfaces and intergranular boundaries, and, as a result, rise of internal stresses and crack formation (Figure 2).

Effect of structure and phase composition of metal. Effect of specific structure-phase constituents on general change of strength characteristics, impact toughness as well as crack resistance of the welded joints was determined based on example of welding of high-strength steels during experimental investigations and further analytical estimations. These steels characterize by wide variety of phase constituents in the joint structure (ferrite F, upper bainite B_u, lower bainite B_l and martensite M). Differential contribution of the various typical structures in change of strength properties and fracture toughness was evaluated based on well-known dependencies of Hall–Petch, Orowan, Krafft etc., whereas, the crack resistance (depending on structures) was evaluated (in accordance with dependencies of Stroh, Conrad) on nature of formation of dislocations in these structures immediately after welding as well as on dynamics of

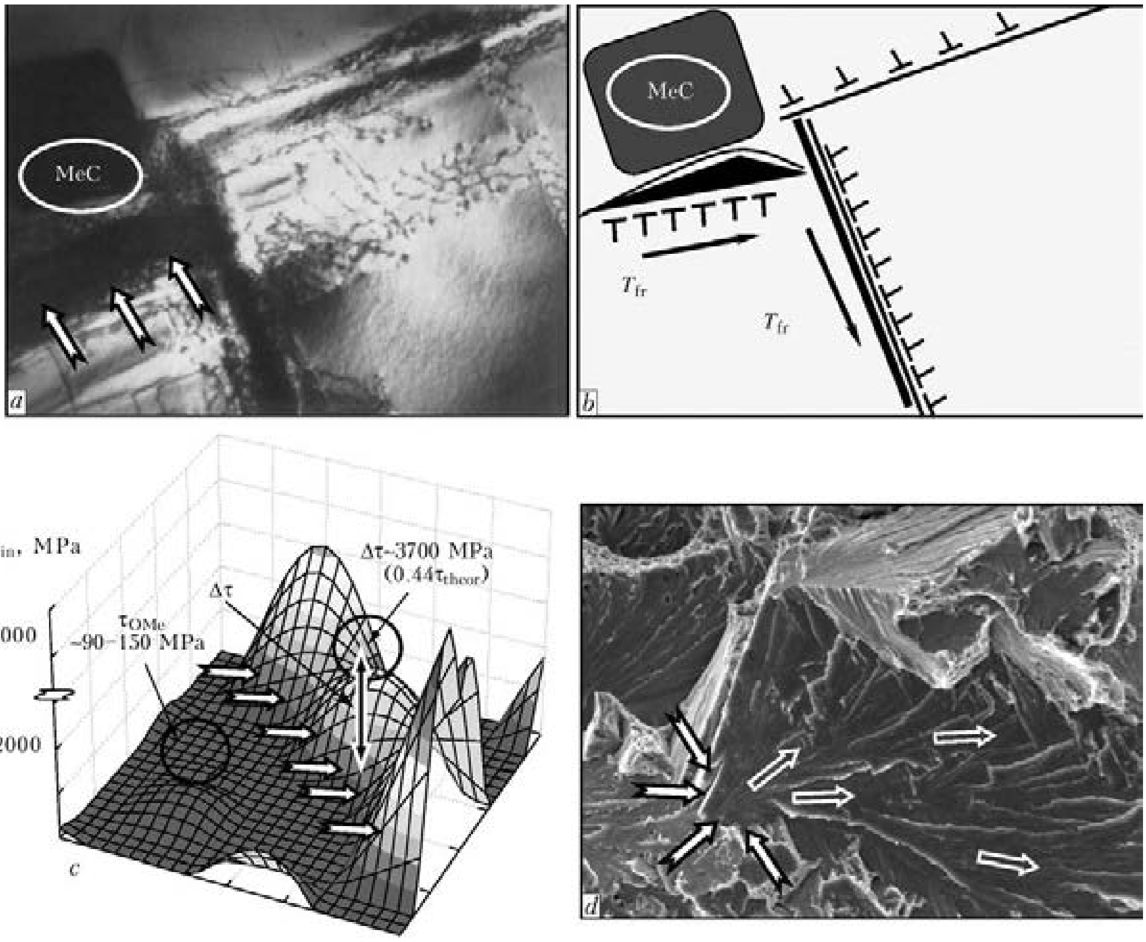

Figure 2. Carbide phases of coarse size as $\tau_{l.in}$ concentrators at intergranular boundaries: *a* — carbide phases at intergranular boundary (×15,000); *b* — schematic representation of crack nucleation in this zone; *c* — $\tau_{l.in}$ rise and their gradients Δτ along intergranular boundary; *d* — nature of brittle transcrystalline fracture in direction opposite to stress concentrator (×1010)

dislocations at further external loading (static, dynamic, cyclic etc.) [9–12]. Capability of the metal structure constituents to relaxation of increasing local internal stresses by plastic relaxation mechanism or brittle fractures was evaluated depending on distribution of the forming dislocation configurations (and, respectively, intensity of local internal stresses) and their extension.

Thus, problem of increase of strength and crack resistance of the wheels and, respectively, reduction of wear level is still relevant in reconstruction repair of surfaces of railway wheels after long term operation, regardless different technological developments. It, in many respects, depends on welding technology and chemical composition of the deposited metal, i.e. on welding wires providing production of the welds with ferrite-pearlite (F-P) and bainite-martensite (B-M) structures.

The investigations were carried out on specimens of solid-rolled railway wheels (from wheel steel 2 of composition, wt.%: 0.55–0.65 C; 0.5–0.9 Mn; 0.22–0.45 Si; ≤0.1 V; not more than 0.03 P and 0.035 S acc. to GOST 10791–89) after reconstruction repair. Mechanized CO_2 welding using Sv-08G2S (F-P weld) and PP-AN180MN (B-M weld) grade wires was used. The results of examination of structure and phase components (F, P etc.), their volume fraction, grain size as well as changes of microhardness of fusion line (FL), HAZ and base metal of railway wheel after reconstruction repair provided the next data.

Application of PP-AN180MN wire from point of view of indices of strength, ductility and crack resistance promoted the optimum structure, which is provided by absence of rapid gradients on size of the structural constituent, uniform phase composition (at transfer from weld metal to wheel steel) and noticeable refinement of structure of the deposited metal (in comparison with F-P weld).

Detailed transmission examinations of weld and HAZ metal, depending on composition of deposited metal, showed the peculiarities of thin structure change (substructure, dislocation density etc.) (Figure 3). The most obvious structural changes in using of Sv-08G2S wire take place at

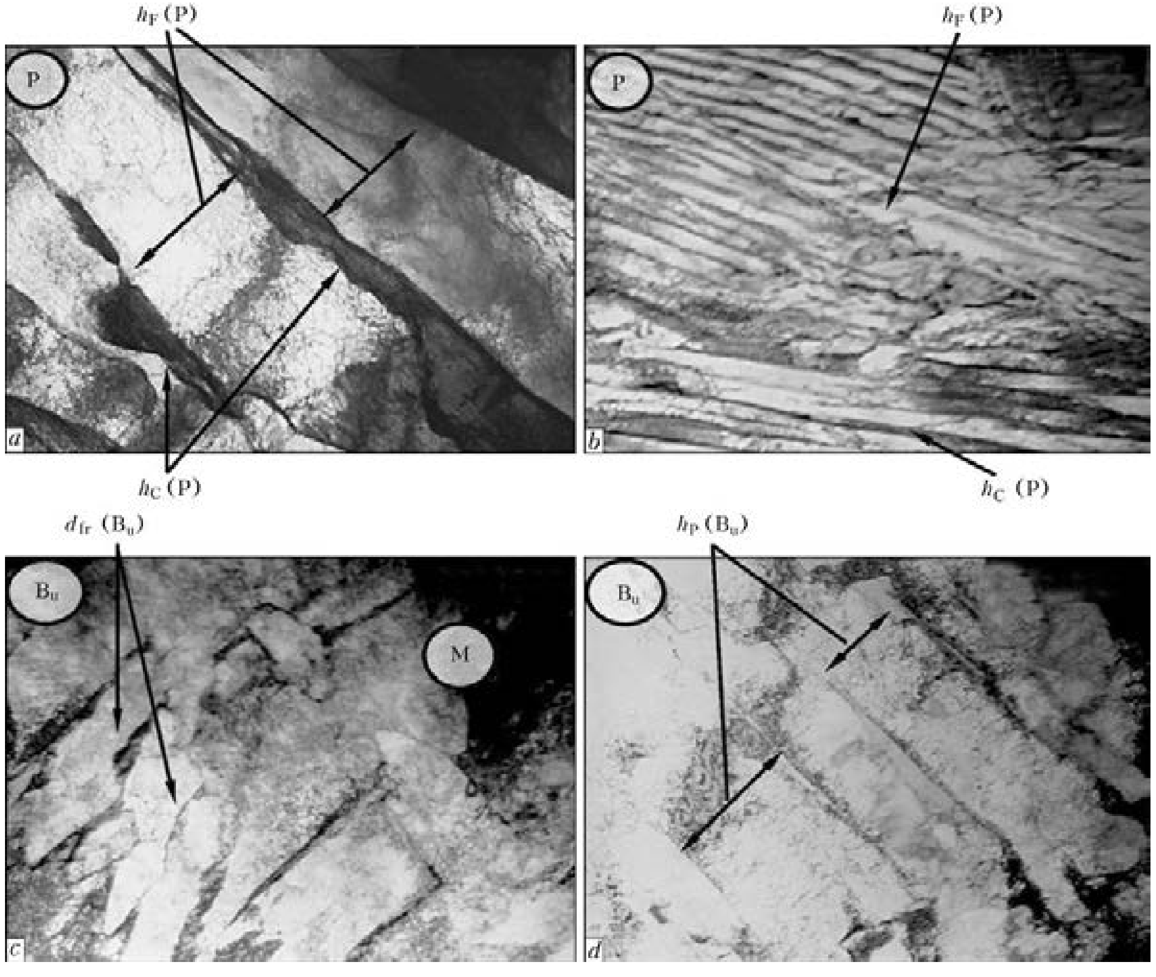

Figure 3. Fine structure of different zones of wheel steel 2 joints in welding using Sv-08G2S (*a*, *b*) and PP-AN180MN (*c*, *d*) wires: weld metal at distance δ ~ 4000 (*a*, *c* — ×20,000) and ~ 500 μm (*b* — ×30,000) from FL; *d* — HAZ area of coarse grain (×30,000)

transfer from weld metal (i.e. deposited metal) to HAZ (to wheel steel) due to rapid refinement of width of ferrite laths (h_F) and cementite plates (h_C) of pearlite structure and increase of dislocation density. This possibly will result in significant strengthening in the fusion zone (from weld side) as well as promote formation of the local stress concentrators being the reason of crack formation (Figure 3, *a*, *b*).

Weld metal (Figure 3, *c*) with B-M structure consisting of B_u, B_l, M and ferrite fringes (F_f) is characterized by formation of the disperse fragmented bainite structure with fragment sizes $B_l(d_{fr})$ of around 0.15–0.50 μm at uniform distribution of the dislocation density approximately $5\cdot(10^{10}–10^{11})$ cm^{-2}. The width of laths of bainite and martensite structures makes $h_{B_u} \approx$ ≈ 0.5–1.2, $h_{B_l} \approx 0.4–0.7$ and $h_M \approx 1.0–1.5$ μm, respectively. The parameters of thin metal structure of area I of HAZ virtually do not change (Figure 3, *d*) at transfer into wheel steel, and uniform distribution of the dislocation density is also observed that, obviously, should promote the optimum combination of strength properties, ductility and absence of the local stress concentrators, i.e. crack formation sources.

Experimental database, obtained as a result of examinations at all structural levels (from macro to micro) allowed carrying out the analytical estimations of the most significant mechanical and service characteristics of the welded joints of wheel steel 2 depending on wire composition. It was shown that total (general) strengthening of weld metal ($\Sigma\sigma_y$ ~ 480 MPa) in the joints welded by Sv-08G2S wire (Figure 4, *a*) was mainly caused by effect of cementite plates ($\Delta\sigma_{d.s}$ ~ 190–230 MPa) of pearlite constituent, and $\Sigma\sigma_y$ rapidly (1.5 times) increases to ~ 800 MPa in approaching to HAZ in local zone of transfer from weld to FL (at depth of about 500 μm from FL) due to rise of contribution of substructure ($\Delta\sigma_s$ to ~ 300 MPa) and dislocation ($\Delta\sigma_d$ to ~ 60 MPa) strengthening.

Smooth change of the general level of strengthening $\Sigma\sigma_y$ from ~ 827–885 (weld metal) to ~ 857 MPa (HAZ area I) takes place in the welded joints, produced with PP-AN180MN wire (Figure 4, *b*) in area of transfer from weld to

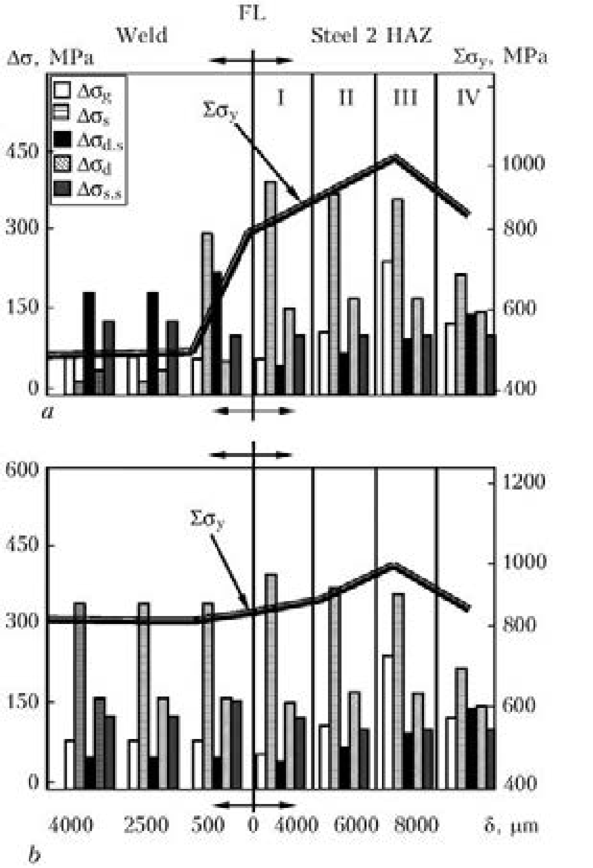

Figure 4. Differential contribution of various structural constituents $\Delta\sigma$ in integral value of strengthening $\Sigma\sigma_y$ of metal of wheel steel 2 joints in welding using Sv-08G2S (*a*) and PP-AN180MN (*b*) wires: I–IV — overheating, normalizing, incomplete recrystallization and recrystallization areas of HAZ

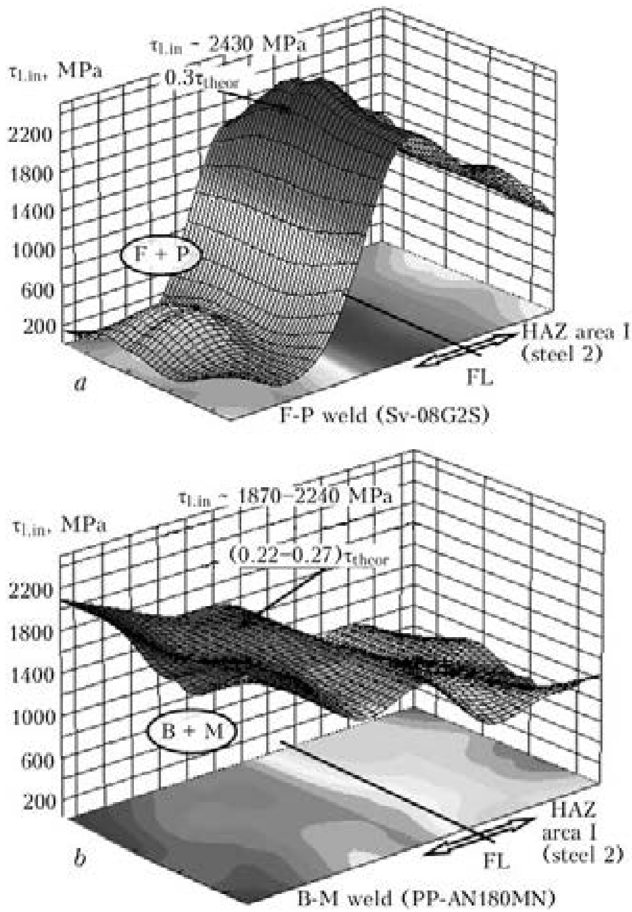

Figure 5. Level of local internal stresses forming in different zones of wheel steel 2 joints, depending on composition of deposited metal: *a* — Sv-08G2S; *b* — PP-AN180MN wire

HAZ. The largest contribution in the integral strengthening is made by substructure ($\Delta\sigma_s \sim$ ~ 345 MPa), carbide phase particles ($\Delta\sigma_{d.s} \sim$ ~ 75 MPa) and rise of general dislocation density ($\Delta\sigma_d$ ~ 140–200 MPa) due to B_l and M constituents. Thus, comparison of the strengthening effect of all forming structures in the investigated F-P and B-M welds allowed determining the most significant on effect structural factors, which are the B_l structures in given case.

The following was shown by the results of calculation estimations of fracture toughness K_{1C} for F-P and B-M welds as well as analysis of K_{1C} and σ_y relationship. It is determined that K_{1C} value is somewhat higher (on average by 20 %) in welding using PP-AN180MN wire (B-M welds) that is caused by grain size refinement, formation of substructure and uniform dislocation distribution. High strength level is also observed that indicates good combination of strength and ductile characteristics of the welded joint. Low K_{1C} index is typical for F-P weld that is related with formation of the coarse grain pearlite constituent, gradient on grain structure size.

Calculation estimations of $\tau_{l.in}$, in comparison of these values with theoretical strength of the material, are given in Figure 5 and show the following. The lower general level of local internal stresses distributed in weld is formed in the joints, produced by Sv-08G2S wire (Figure 5, *a*). $\tau_{l.in}$ value approximately corresponds to 200–400 MPa that makes ~ $0.04\tau_{theor}$. Rapid (by order) increase of the dislocation density from ~ $(4–6)\cdot10^9$ cm^{-2} to ~ $(5–8)\cdot10^{10}$ m^{-2} in approximation to HAZ (at ~ 500 μm depth from FL) and transfer to wheel steel (HAZ area I) results in formation of gradients ($\tau_{l.in}$ ~ 2000 MPa) of the internal stresses (relatively to weld metal). The maximum values of inner stresses structurally initiated by local dislocation accumulations, define $\tau_{l.in}$ of 2240–2430 MPa order, that make $(0.3–0.4)\tau_{theor}$.

Using of PP-AN180MN wire (Figure 5, *b*) provides higher $\tau_{l.in}$ values in the weld metal of 1870–2240 MPa order that makes around $0.25\tau_{theor}$. It is shown that $\tau_{l.in}$ distribution in B-M weld has gradientless nature and uniformly reduce (to 900–1000 MPa) at transfer in HAZ metal of wheel steel 2. Thus, B-M structure,

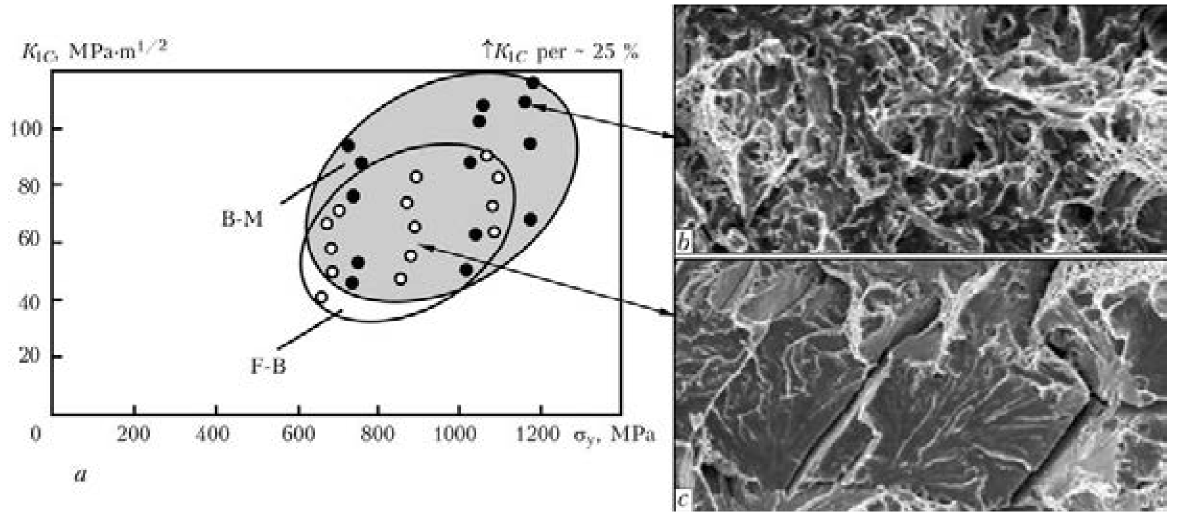

Figure 6. Comparison σ_y and K_{1C} values of welded joints of steel 17Kh2M (*a*), and nature of their fracture depending on type of welding wire (×600); *b* — F-B; *c* — B-M weld

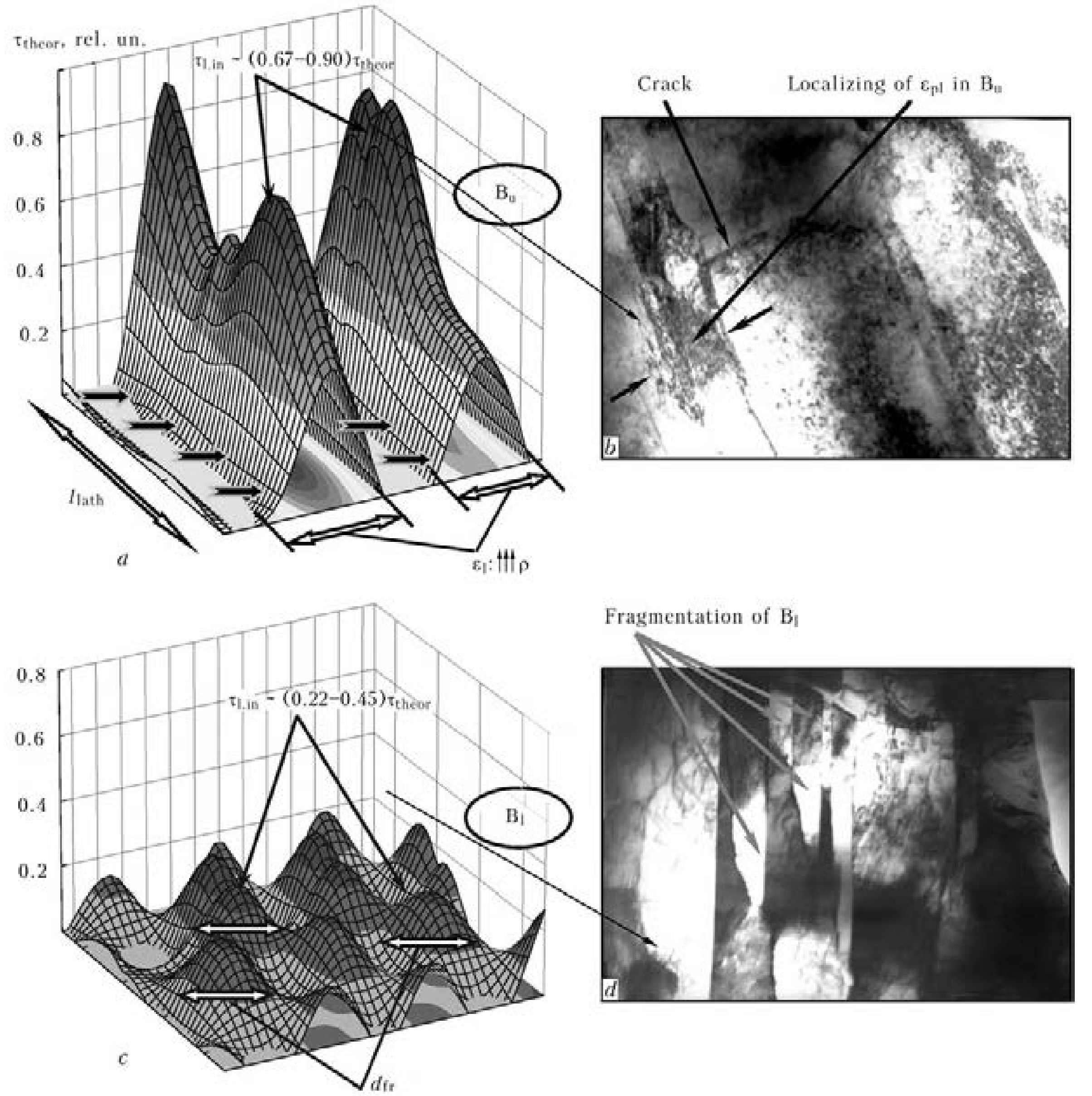

Figure 7. Estimation of $\tau_{l.in}$ values in comparison with τ_{theor} values, and corresponding structure (×30000) of upper (*a*, *b*) and lower (*b*, *d*) bainite

forming from weld metal side as well as wheel steel side (HAZ area I) is characterized by the most uniform distribution of local internal stresses, absence of their gradients and do not provoke crack formation.

Thus, the most optimum on service characteristics (strength, ductility, crack resistance) is application of PP-AN180MN wire in formation of B-M type structure. It was demonstrated by the investigations of structural parameters of joint metal, being formed in reconstruction repair of railway wheels using wires of different chemical composition (Sv-08G2S and PP-AN180MN) as well as analytical estimation (on the basis of structural examinations) of changes of mechanical properties.

Analytical approach to estimation of the relationship of mechanical properties and crack resistance was also used in investigation of welded joints of high-strength steel 17Kh2M using different wire types Sv-08G2S (F-B weld) and Sv-10KhN2GSMFTYu (B-M weld) (Figure 6).

The results of carried estimations of $\tau_{l.in}$ values as well as relationship of these values with theoretical strength of the material, which are given on diagrams of Figure 7 for different variants of weld metal chemical composition (F-B and M-B type), show the following. The highest $\tau_{l.in}$ values in structure of upper bainite are typical for the F-B weld metal (Figure 7, *a*, *b*). And the lowest values, notably at comparatively uniform their distribution in the welded metal, are observed in the case of joint with M-B weld. The latter, obviously, is promoted (as verified by structural examinations) by formation of fine grain M and B_l structures (Figure 7, *c*, *d*). It can be observed that nature of the structures, formed in using of different on chemical composition of welding wires, significantly effect distribution as well as level of the local internal stresses of welded joint metal.

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