EFFECT OF CYCLIC LOAD ON MICROSTRUCTURE AND COLD RESISTANCE OF THE 10G2FB STEEL HAZ METAL

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Fatigue of structural materials is one of the main reasons of breakdown and failure of machines, mechanisms and engineering structures. Fatigue cracks in the welded joints are mainly nucleated in a HAZ, and process of their accumulation has long-term and phasic nature. Aim of the present work lies in investigation of effect of cyclic bending load on change of structure and properties of metal of HAZ in the welded joints of C490 strength class structural steel. Dynamics of accumulation of fatigue damages in the metal was investigated, and effect of cyclic load on cold resistance of the metal of HAZ in 10G2FB steel was estimated using model specimens, treated by welding thermal cycle. It is determined that formation of the fatigue cracks in welded joints as well as model specimens is proceeded by the processes of accumulation of fatigue damages in form of stable slip bands of different configuration as well as formation of extrusions and intrusions. The damages, accumulated in HAZ metal of low-alloy structural steels due to fatigue, promote embrittlement of the metal that results in reduction of its cold resistance. The results of investigations can be used as a basis for methods of testing of welded joints in metal structures of long-term operation as well as for taking the decisions on their strengthening or repair. 15 Ref., 9 Figures.

Keywords: *arc welding, 10G2FB steel, welding thermal cycles, model specimens, heat-affected zone, cyclic bending load, structural changes, fatigue cracks, impact toughness*

It is a well-known fact that one of the main reasons of breakdown and failure of machines, mechanisms and engineering structures is fatigue of structural materials [1], which results in formation of the fatigue cracks in separate part assemblies, having the greatest loading [2]. Typically, such assemblies in the welded joints are specific zones, which mainly include structural stress concentrators [2]. By now, number of accidents due to specified metal condition is still large, regardless the significant success in study of mechanisms of the fatigue processes and development of methods for increase of life duration of the welded metal structures. Therefore, specific practical interest is paid to investigation of the processes and reasons reducing life duration of the materials under service conditions, in particular, with regard to fatigue damage of the structures, which is evidenced by publications of the recent years [3–7].

The E.O. Paton Electric Welding Institute also carries out such works [8–11]. In particular, work [10] shows that accumulation of the fatigue damages and fatigue changes under conditions of cyclic bending load of the welded joints from low-alloy structural steel 09G2S are mainly localized in metal of HAZ and adjacent to it areas of the base metal. As a result, the metal becomes brittle and its cold resistance reduces by 20–40 %.

However, there are some difficulties in investigation of the reasons of fatigue damages directly on the welded joints. They are related with simultaneous effect of series of technological and structural conditions, among which the most important are inhomogeneity of structure and, respectively, properties of the metal in different zones of the welded joints varying in chemical and phase composition, as well as changes of welding modes, weld geometry, external load conditions etc. Eventually, a complex of structural, technological and external parameters promotes, particularly, appearance of significant errors in the results of investigations.

Considering complexity of the factors, promoting fatigue damages, a stepwise approach is taken for investigation of effect of cyclic load on the structure and, respectively, cold resistance of the HAZ metal of structural steel. It provides for successive study of conditions of damage accumulation in the welded joints (by making notches of different depth δ), effect of rise of cyclic load (frequency, stress σ_{-1} and increase of number of cycles N). At that, the whole complex of investigations was carried out only using model specimens that ensure consistency of chemical composition in examined zones of the welded joints, and process stability was provided by conditions of simulation of welding thermal cycle.

Materials and investigation procedures. The simulation of welding thermal cycles (heating and cooling in accordance with the modes which take place in HAZ metal of the real welded joints) using model specimens of 20 × 20 × 120 mm size (steel 10G2FB) was carried out on special unit of MSP-75 type, designed at the E.O. Paton Electric Welding Institute on the basis of machine for resistance welding. It allows simulation of real welding cycles through specimens heating using passing current and cooling by compressed air.

Heating rate of the specimens in simulation of welding cycles (specimens were heated to 1100 °C) made 150 °C/s, and cooling rate in the range of 600–500 °C was $w_{6/5}$ = 10 °C/s. After treatment of the specimens on welding thermal cycle for simulation of geometry stress concentrator, which is usually observed in the welded joints at weld to base metal transition, notches of 2 mm width and 1 mm rounded radius near its tip were made of the surface of 20 × 20 × × 60 mm size specimens. At that, notches of 1, 3.5 and 7 mm were made on the specimens at initial stage of the investigations (in elaboration of the most optimum evaluation procedure) that allowed determining, which of the specimens would reflect real structural processes (slip systems, cracks etc.), indicating accumulation of the damages taking place in the joints.

Fatigue testing of the model specimens was carried out on low-duty fatigue machine of UMM-1 type. The specimens were subjected to cyclic bending load with symmetric cycle at 35 Hz frequency and cycle stress σ_a = 120 MPa.

Structural changes under effect of different conditions of loading were studied using complex of the investigation methods, namely optical metallography (Versamet-2), analytical scanning electron microscopy (Philips SEM-515, Netherlands) and light electron microscopy (JEOL JEM-200CX, Japan) with accelerating voltage 200 kV.

Results of investigation. At the first stage, nature and distribution of slip systems on side surfaces of the specimens in corresponding zones of welding were investigated depending on number of load cycles as well as at change of notch depth, made for the purpose of simulation of geometry stress concentrator and, respectively, the conditions of crack formation in the welded joints in zone of weld to base metal transition.

Metallographic investigations showed that the fatigue cracks in specimens with δ = 1 mm were formed after 2 mln 500 thou cycles of load ($0.45N/N_{fr}$, Figure 1, *a*).

Increase of number of load cycles rises an intensity of fatigue damages of the surface of model specimens that indicates increase of amount of stable slip bands as well as appearance of extru-

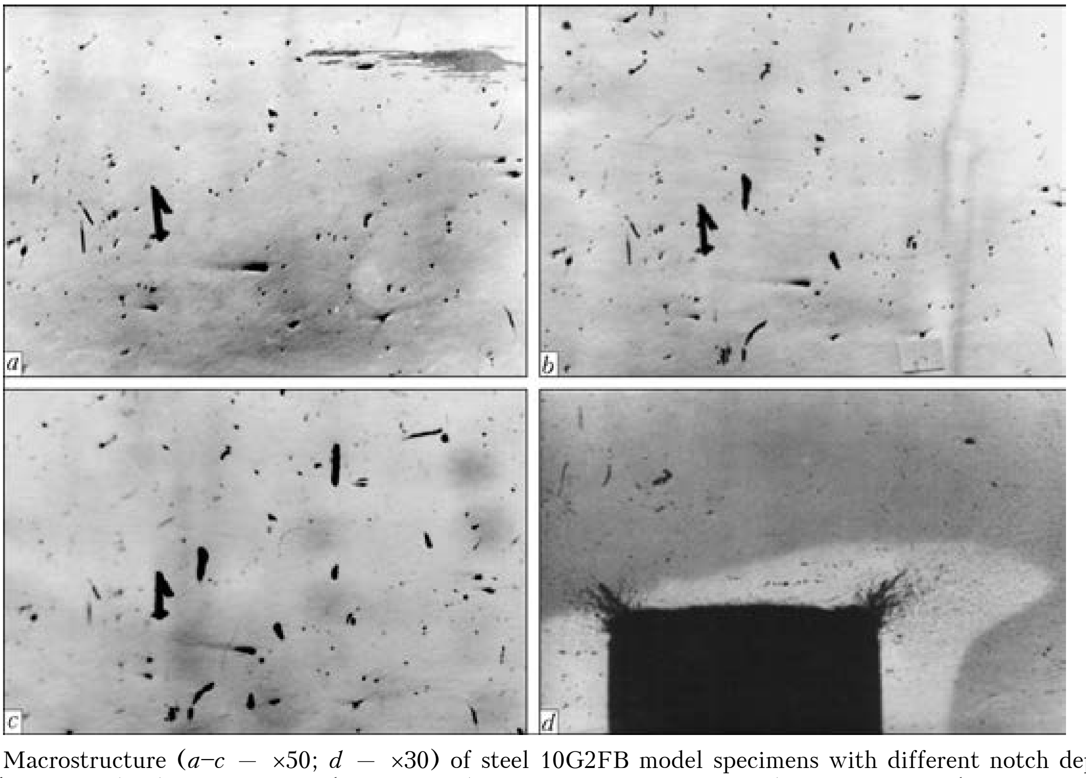

Figure 1. Macrostructure (*a*–*c* — ×50; *d* — ×30) of steel 10G2FB model specimens with different notch depth after cyclic load: *a* — $0.45N/N_{fr}$, δ = 1 mm; *b* — $0.70N/N_{fr}$, δ = 1 mm; *c* — $0.80N/N_{fr}$, δ = 1 mm; *d* — N_{fr}, δ = 3.5 mm

sions and intrusions. Moreover, further loading becomes structurally evident through growth of dimensions of stable slip bands, complication of their configuration as well as increase of distribution frequency of slip bands on the surface of model specimens ($0.70N/N_{fr}$, $0.80N/N_{fr}$) (Figure 1, *b*, *c*). At that, fatigue damages and structural changes in the HAZ metal of specimens developed, as a rule, in certain zones and had local nature. The greatest number of the stable slip bands was observed in central (axial) part of the specimen that, apparently, is caused by high level of stresses acting in this zone in course of cyclic strain.

The similar structural changes, but at earlier stages of cyclic bending load were observed in the specimens with $\delta = 3.5$ mm. The fatigue cracks in these specimens were already formed after $N = 21{,}000$ cycles of load (Figure 1, *d*), proceeded by significant changes in structure of the HAZ metal under notch. Beginning of formation of the stable slip bands in examined specimens was observed after 5000 cycles of load and further increase of number of load cycles promoted growth of density of the stable slip bands.

Completely another situation was observed near the surface of specimens with $\delta = 7$ mm. The fatigue cracks in these specimens have already formed after 4500 cycles of load, nucleation of such type of the cracks takes place immediately under notch and without noticeable (at optical investigations) changes in metal structure.

It is determined, considering the results of investigation of structures with different notch depth, that $\delta = 3.5$ mm is the optimum specimen notch. This allows reproducing all structural changes accompanying the processes, which are studied in the welded joints, as well as accelerating the procedure of specimen preparation to further examination.

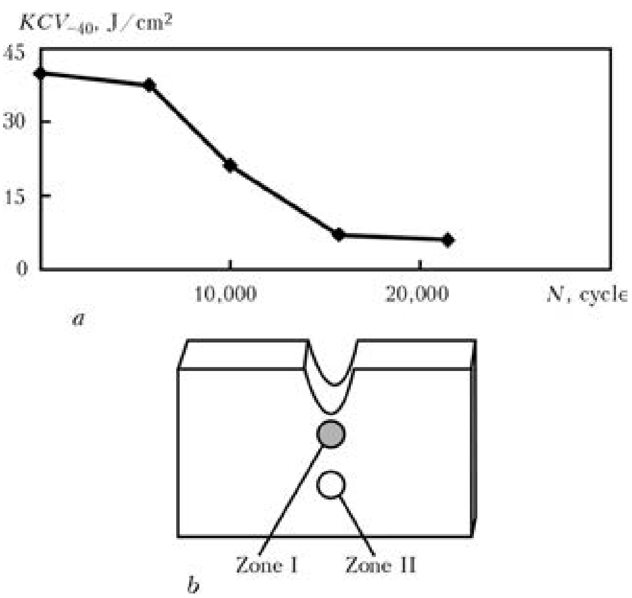

Figure 2. Effect of cyclic load on impact toughness of steel 10G2FB model specimens (*a*), and scheme of specimen with indication of examined zones (*b*)

For this purpose, first of all, effect of the level (number) of cyclic load on nature of plastic strain, formation of fatigue cracks and cold resistance were investigated on the model specimens (particularly with $\delta \sim 3.5$ mm) treated on welding thermal cycle after cyclic load under cycle stress 120 MPa. Loading at $N = 21{,}000$ results in development of 2 mm fatigue crack from notch tip with plastic strain zone, which indicate that these number of cycles is critical one and loading to $N = 7000$, 11,000 and 15,000 makes 33.3, 53.2 and 71.4 % of critical load, respectively.

Impact bending tests of standard specimens with sharp Charpy notch, cut from model specimens after all cyclic loads with notch ($\delta \sim 3.5$ mm) tip orientation in area of plastic strain zone, were carried out in parallel. At that, according to [10] reduction of indices of critical stress intensity factor K_{1c} and critical crack opening in HAZ metal takes place at negative temperatures, therefore, the tests of specified specimens were carried out at −40 °C. As can be seen from Figure 2, *a*, the values of impact toughness in the initial condition after treatment on welding thermal cycle, as well as cyclic load to 7000 in tested specimens, were sufficiently similar (37–40 J/cm²). Increase of load cycles promotes irregularity of such uniformity. Cold resistance of model specimens reduces gradually to 18–22 J/cm² after 11,000 cycles and to 7–8 and 4.5–6 J/cm² after 15,000 and 21,000 load cycles, respectively. Thus, impact toughness of the specimens from steel 10G2FB reduces 1.8, 4.9 and 7.5 times under given conditions of cyclic load in comparison with initial conditions ($N = 0$).

The second stage of work lied in structural examinations, aim of which was determination of the initial structure before loading under conditions of growth of cyclic load as well as determination of peculiarities of structural changes, accompanying crack formation.

Change of structural composition, first of all, phase constituents, dimension of their grains, microhardness, as well as such parameters of fine structure as dimensions of subgrains, width of laths, density and distribution of dislocations in the model specimens were examined in two specific zones, namely I — under notch (zone of maximum loading), and II — in the center of specimen (see Figure 2, *b*).

Initial structure condition. Structure of metal in the specimens treated on welding thermal cycle, but did not subjected to cyclic load (initial

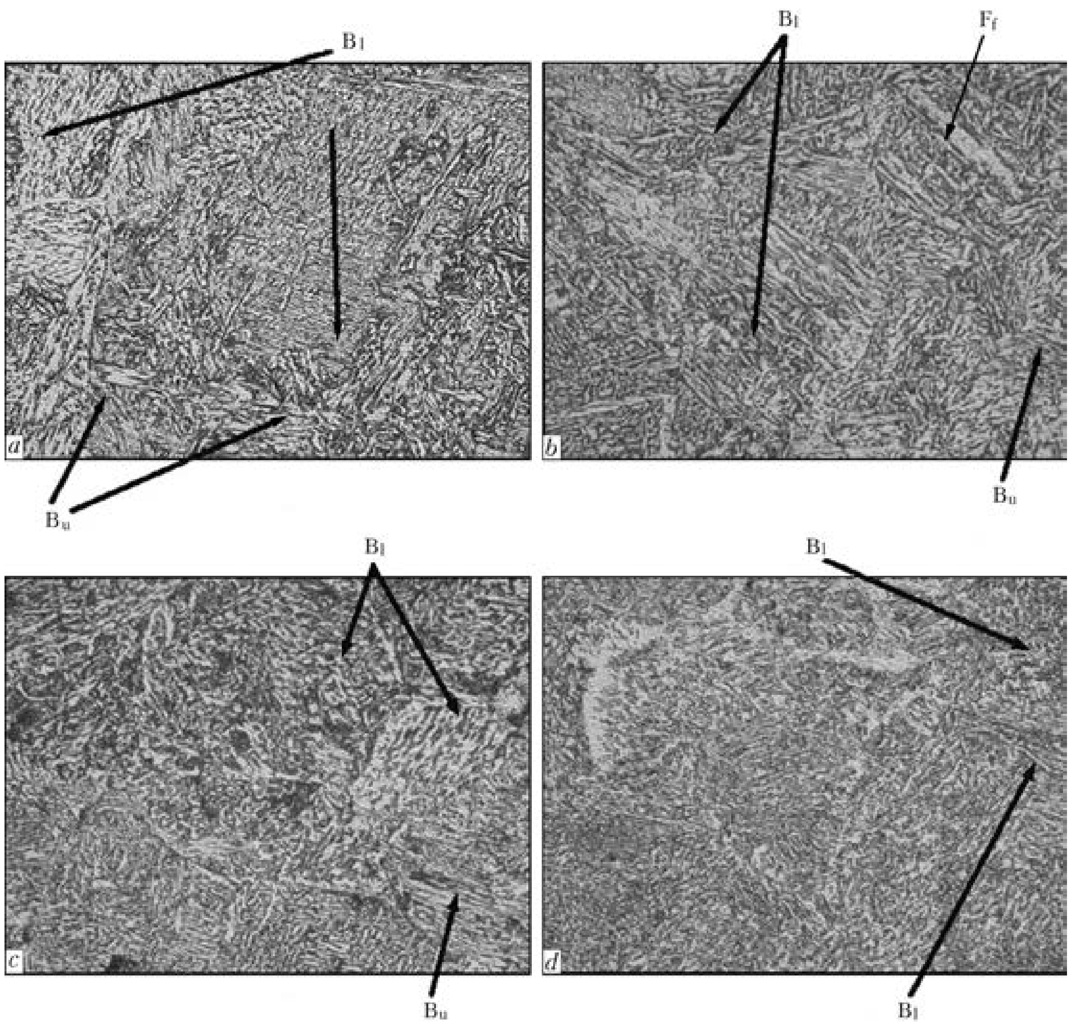

Figure 3. Microstructure (×500) of metal of steel 10G2FB model specimens in HAZ overheating area in initial condition (*a*, *b*) and after 21,000 cycles of load (*c*, *d*) under notch (*a*, *c*) and in the specimen center (*b*, *d*)

condition), was investigated. The structure under notch (zone I) as well as in the center of specimen (zone II) is represented by upper bainite (B_u), lower bainite (B_l) and ferrite fringes (F_f) (Figure 3, *a*, *b*). In zone I dimension of upper bainite grain D_g lies in the range of 100–250 μm (Figure 4, *a*). Dimension of lower bainite grain changes from 80 to 180 μm and width of ferrite fringes is from 5 to 10 μm. Microhardness *HV* of upper bainite takes 2370–2470 MPa range and that for lower bainite is 2630–2830 MPa.

Metal structure similar on phase composition (in initial condition) was formed in the center of specimen, but it has somewhat another parameters and microhardness. Rise of dimensions of grain of structural constituents, namely upper bainite by 16 % (to 130–290 μm) and lower bainite by 26 % (to 120–230 μm) is observed in zone II in contrast with zone I, whereas their microhradness reduces by 5 % (Figure 4, *c*). Dimension of ferrite fringes in these zones remains the same.

Investigation of fine metal structure in zones I and II at initial condition using transmission microscopy determined (Figures 4, *b*, *d*; 5, *a*, *b*) that width of lath h_l for upper bainite reduces in zone I in comparison with corresponding parameters in zone II by 13 % and makes h_l ~ 0.5–1.8 μm, i.e. dimensions of dislocation substructure d_s also reduces, mainly with substructures of lower bainite in zone I (almost 1.4 times reduction to ~ 0.5–0.8 μm dimension). As for values of inside-volume dislocation density ρ, then, concerning different structural constituents (and for B_u and B_l) lager increase of dislocation density is typical for zone I, i.e. for zone with maximum loading (Figure 4, *b*). It is typically that volume dislocation density rises to lager extent in lower bainite structures, for which $\rho \sim 5\text{–}7\cdot10^{10}$ cm^{-2}, and $\rho \sim (3\text{–}5)\cdot10^{10}$ cm^{-2} for upper bainite.

Cyclic load. Transformation of structural constituents takes place in the process of further cyclic load of the examined metal directly under notch (zone I). In comparison with initial condition, reduction of the dimension of upper bainite grain is observed on average by 4, 11 and 20 % after 7000, 15,000 and 21,000 cycles of load,

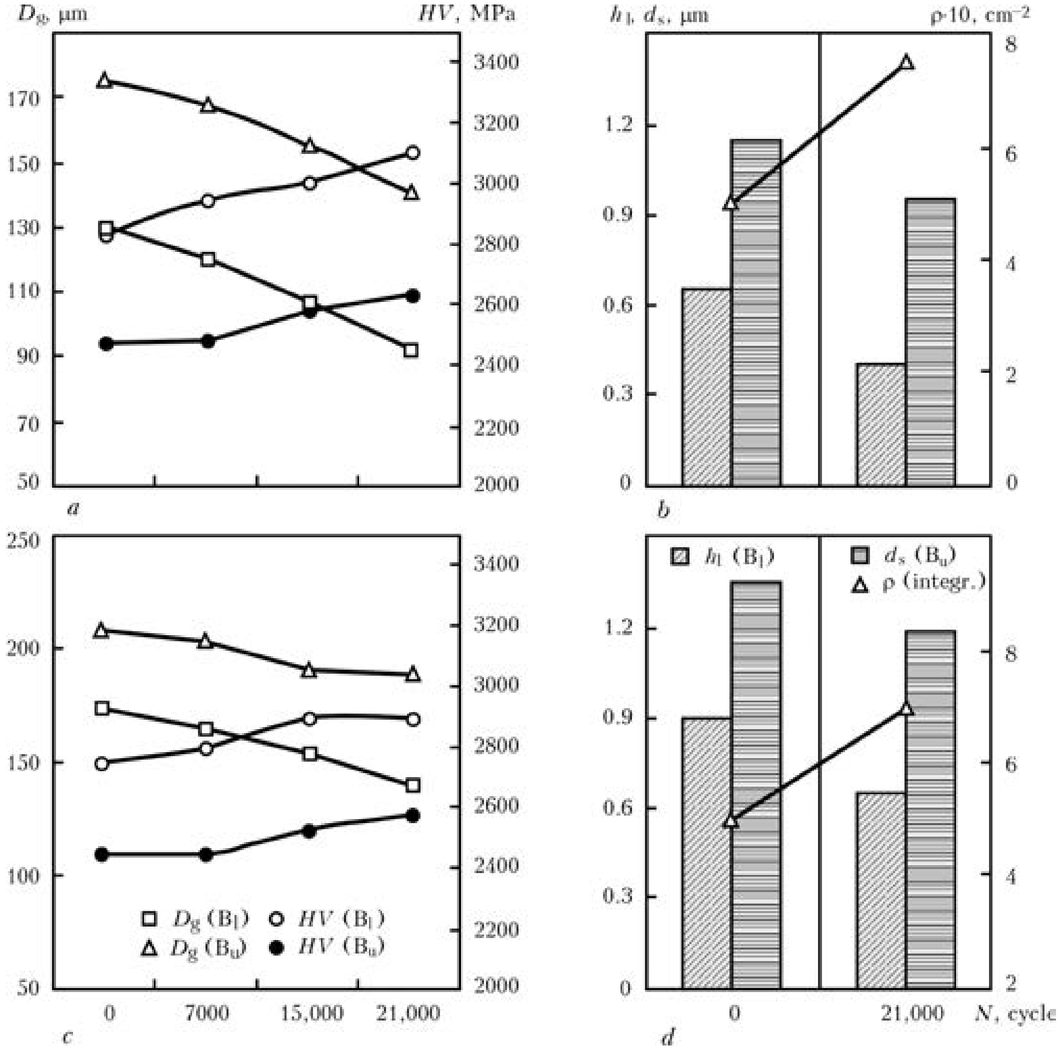

Figure 4. Dependence of average grain size and maximum values of microhardness (*a*, *c*), lath width and dislocation density (*b*, *d*) in structural constituents of metal of steel 10G2FB model specimens under notch (*a*, *b*) and in the center specimen (*c*, *d*) on number of load cycles

respectively (Figure 4, *a*). Similarly, 8, 18 and 30 % decrease of the dimensions of lower bainite grains takes place. At that, width of ferrite fringes remains the same.

Values of microhardness for upper bainite structures are, virtually, at the level of initial ones (without cyclic load) (2360–2500 MPa) at minimum number of load cycles at the level of around 7000, whereas they are somewhat higher (up to 2570–2940 MPa) for lower bainite. Inhomogeneity of the microhardness indices of indicated structural constituents (B_u, B_l) are also observed at increase of number of load cycles to N ~ 15,000 and this tendency is preserved (Figure 4, *a*, *c*) with maximum number of load cycles (up to 21,000).

Examination of changes of fine metal structure in zone I during deformation process determined that cyclic load (from initial to $N = 21,000$) promotes reduction of the structure dimensions in comparison with initial one (1.6 times, i.e. by 38 %) as well as decrease of the dimensions of upper bainite laths 1.2 times, i.e. by 17 %. Besides, approximately, 1.4 times increase (from $6\cdot10^{10}$ to $8.5\cdot10^{10}$ cm^{-2}) (see Figure 4, *b*) of total volume density of the dislocations takes place in wrought metal. At that, formation of intergranular dislocation substructure, i.e. fragmentation of structure (Figure 5, *d*) with clear subboundaries and higher scalar dislocation density (ρ ~ ~ $(7-9)\cdot10^{10}$ cm^{-2}), is observed in the structures of lower bainite, that is higher of the corresponding values in the structures of upper bainite (ρ ~ $(5-8)\cdot10^{10}$ cm^{-2}) (Figure 5, *c*).

Similar dependencies in transformation of the structural constituents, taking place as a result of effect of external cyclic bending load, is observed in the metal in specimen center (zone II). It was also found in this case that increase of number of load cycles promotes reduction of grain dimensions of upper and lower bainite in the following order, namely by 3 and 6 % after 7000 cycles, by 8 and 11 % after 15,000 and by 10 and 20 % after 21,000 cycles, respectively. Micro-

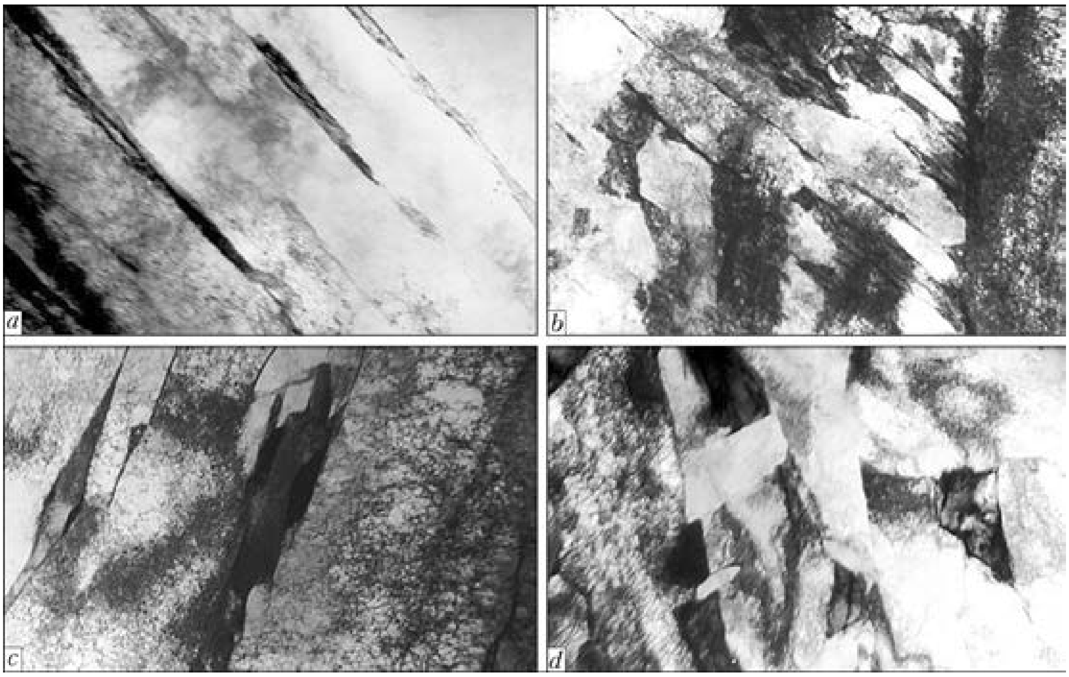

Figure 5. Microstructure (×1500) of metal of steel 10G2FB model specimens in initial condition (*a*, *b*) and after 21,000 cycles of load (*c*, *d*) in zone I: *a*, *c* — laths of upper bainite; *b*, *d* — fragments of lower bainite

hardness of the structural constituents in zone II shows increase for upper and lower bainite (see Figure 4, *c*) with rise of number of cycles.

More detailed transmission examinations of zone II fine structure showed that width of laths of upper bainite at $N = 21{,}000$ reduces 1.1 times (by 11 %) in comparison with initial condition, and dimensions of fragments of lower bainite decreases, approximately, 1.4 times, i.e. by 27 %. Total volume density of dislocations in given zone also rises from $4\cdot10^{10}$ to $6.5\cdot10^{10}$ cm^{-2}, i.e. 1.5 times.

It is interesting to note that the greatest dislocation density is observed along the boundaries of upper bainite laths in zone I. It rises up to $2.5\cdot10^{11}$ cm^{-2} in separate zones after 21,000 cycles, that results in appearance of clear zones of deformation localizing and, obviously, is one of the main reasons of crack formation (Figure 6).

Performed complex of experimental investigations was used for estimation of differential effect of structural parameters of HAZ metal of 10G2FB steel deformed under cyclic load on change of main service characteristics of examined specimens, i.e. static strength, fracture toughness and crack resistance. Analytical estimation of integral value of yield strength $\Sigma\sigma_y$ was carried out using equation, including known dependencies of Hall–Petch, Orowan and others:

$$\Sigma\sigma_y = \Delta\sigma_0 + \Delta\sigma_{s.s} + \Delta\sigma_g + \Delta\sigma_s + \Delta\sigma_d + \Delta\sigma_{d.s},$$

where $\Delta\sigma_0$ is the resistance of metal lattice to movement of free dislocations; $\Delta\sigma_{s.s}$ is the strengthening of solid solution with alloying elements; $\Delta\sigma_g$, $\Delta\sigma_s$ is the strengthening due to change of value of grain and subgrain; $\Delta\sigma_d$ is the dislocation strengthening; $\Delta\sigma_{d.s}$ is the dispersion strengthening. The examples of calculation are given in works [12, 13].

It is shown as a results of analytical estimation of metal yield strength (Figure 7), that $\sigma_y \sim$ ~ 541 MPa in initial condition in zone II after treatment on welding thermal cycle. In zone I this index is little bit higher ($\sigma_y \sim 644$ MPa) that can be related with more intensive deformation of metal during notch performance. Yield strength of metal increases as a result of cyclic load (after 21,000 cycles) in zone I, as well as in zone II by 16–20 % to 671 and 771 MPa, respectively. The main contribution in rise of σ_y integral value makes strengthening due to refining of substructure ($\Delta\sigma_s \sim 243$–283 MPa), mainly

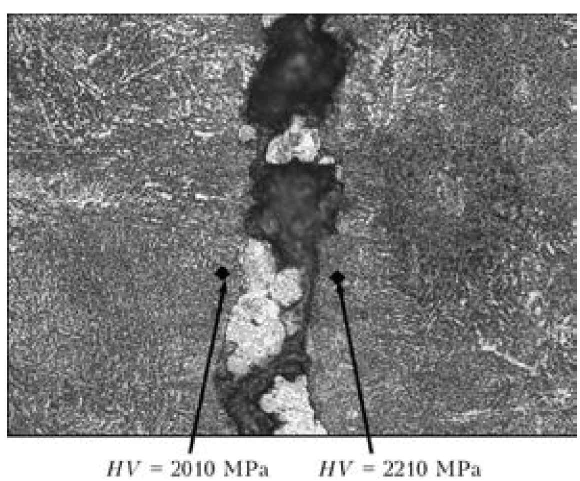

Figure 6. Fatigue crack (×320) formed in the specimen under notch (zone I) after 21,000 cycles of load

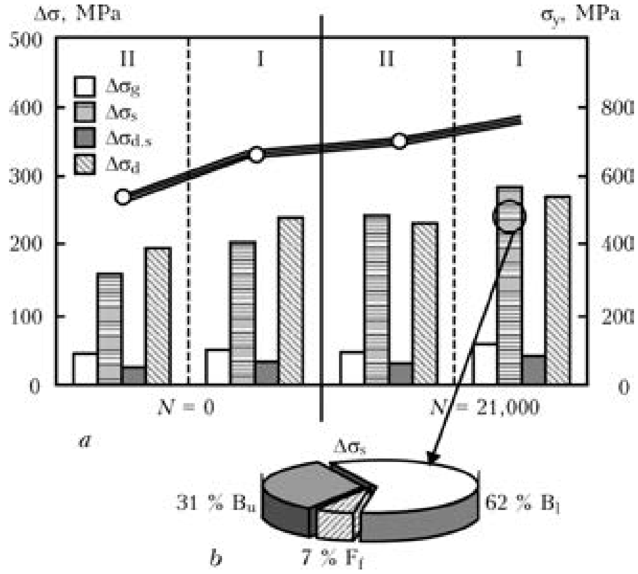

Figure 7. Contribution of separate structural parameters in integral strengthening (*a*) and structural constituents in substructure strengthening (*b*) of metal of steel 10G2FB model specimens in initial condition and after 21,000 cycles of load

in the structures of lower bainite (up to $\Delta\sigma_s$ ~ ~ 159–188 MPa) as well as dislocation strengthening structures (up to $\Delta\sigma_d$ ~ 230–270 MPa). Grain structure ($\Delta\sigma_g$ ~ 47–57 MPa) and dispersion strengthening ($\Delta\sigma_{d.s}$ ~ 31–41 MPa) have the minimum effect on strengthening (Figure 7).

It should be noted that the calculated values of metal yield strength sufficiently well correlate with σ_y values, received in investigation of effect of cooling rate on structure and properties of 10G2FB steel [2]. It was determined in course of these investigations that metal indices in HAZ overheating area lie in 550 MPa level at $w_{6/5}$ = = 10 °C/s cooling rate.

The value of critical stress intensity factor (index of fracture toughness) was determined in accordance with Krafft dependence, given in [14]:

$$K_{1c} = (2E\sigma_y\delta_i)^{-1/2},$$

where δ_i is the crack tip opening, mm, received on data of fractographic analysis of fractures; E is the Young's modulus, MPa.

Analytical estimation of critical stress intensity factor verified a mechanism of reduction of K_{1c} indices, obtained as a result of testing of specimens of butt and T-welded joints, described in work [11]. The latter shows that the values of fracture toughness reduces from 47 initial condition to 35 MPa·m$^{1/2}$ after 21,000 cycles, i.e. 1.3 times (Figure 8), under notch. It is, obviously, related with general increase and inhomogeneous distribution of the dislocation density in upper bainite structures.

In addition to mentioned above analytical estimations of contribution of structures in change of strength and fracture toughness of the metal, effect of some structural factors on such process as crack formation and providing of crack resistance of examined welded joints operating under complex conditions of cyclic load was also determined. Estimations of the local internal stresses $\tau_{l.int}$ in specific examined zones, considering dislocation density in typical structural constituents, were carried out using dependence, calculation of which is given in [15]:

$$\tau_{l.int} = Ebh\rho/(\pi(1 - \nu)),$$

where b is the Burgers vector; h is the foil thickness, μm; ν is the Poisson coefficient.

As examination of the dislocation structure showed, increase of number of cycles (up to 21,000) in examined areas of the metal, first of all, in zone I of the wrought metal, provides for formation of extended dislocation accumulations with high dislocation density (to $\rho \sim 2\cdot10^{11}$ cm^{-2}) which, as a rule, are distributed along cementite intergrain boundaries of the upper bainite. The level of local internal stresses in indicated dislo-

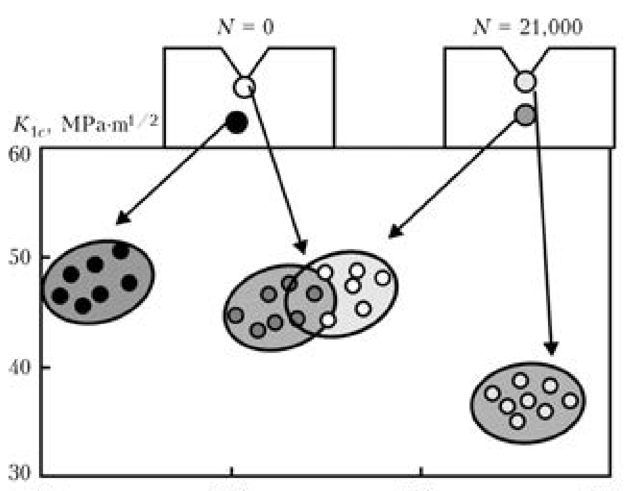

Figure 8. Relationship between yield strength σ_y and stress intensity factor K_{1c} of metal of steel 10G2FB model specimens in initial condition and after 21,000 cycles of load

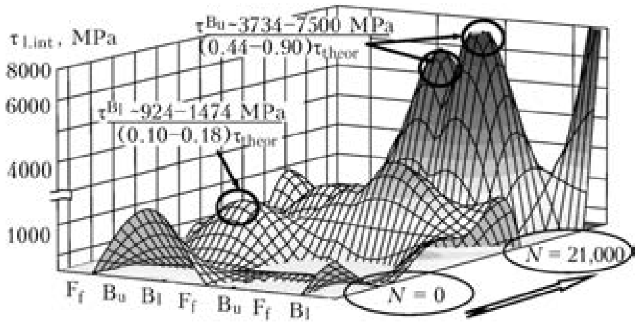

Figure 9. Calculated values of local internal stresses in different structural zones of metal of steel 10G2FB model specimens in initial condition and after 21,000 cycles of load

cation accumulations in some cases achieves around 3730–7500 MPa ($(0.44–0.90)\tau_{theor}$). This is an evidence of the fact that areas of the compact extended dislocation accumulations of specified type are the potential zones of nucleation and propagation of cracks (Figure 9). Another nature of the dislocation distribution under conditions of cyclic load is observed in the structures of lower bainite, where dislocation density makes approximately $(7–9)\cdot 10^{10}$ cm^{-2} at their uniform distribution in the internal lath volumes. This, respectively, results in redistribution and significant decrease of the level of local internal stresses to 924–1474 MPa, i.e. approximately, to $(0.10–0.18)\tau_{theor}$. The latter fact indicates that formation of the lower bainite structures in the HAZ metal of welded joints from 10G2FB steel provides for increase of their crack resistance and, respectively, safety of the metal structures, operating under complex load conditions.

Conclusions

1. Notch of 3.5 mm depth was taken as the optimum one in course of performance of experiments on HAZ metal of welded joints from high-strength steel 10G2FB under conditions of rise of cyclic fatigue load at parallel examination of structural changes in corresponding zones of metal. Larger notch depth (7 mm) promotes formation of the fatigue crack without obvious signs of accumulation of the fatigue damages. At reduction of notch depth (1 mm), duration of all processes, proceeding fatigue crack formation, significantly increase in time.

2. Formation of the fatigue cracks is accompanied by development of specific mechanisms of plastic strain, as well as accumulation of damages in form of stable slip bands of various configuration, extrusions and intrusions having significant effect on the welded joint properties.

3. Structural investigations determined that rise of number of load cycles (after 7000, 15,000 and 21,000, respectively) promotes decrease of grain dimensions of upper bainite by 4, 11 and 20 %, and also dimensions of lower bainite grains by 8, 18 and 30 %, as well as dimensions of substructure (1.4–1.6 times) at increase of total dislocation density (1.4–1.5 times) in comparison with the initial condition.

4. Analytical estimations of effect of the structures formed in the process of cyclic load on indices of main service characteristics, i.e. strength, fracture toughness and crack resistance, were carried out based on complex examinations, including optic metallography, scanning and light electron microscopy. Increase of indices of HAZ metal yield strength by ~ 16–20 % is observed with rise of number of bending load cycles, and the main contribution in improvement of the strength characteristics is introduced by substructure and dislocation strengthening. At that, fracture toughness reduces almost 1.3 times.

5. Formation of the structures of lower bainite type promotes increase of crack resistance of the examined welded joints that is caused by development of complex conditions of loading typical for given type of fragmentation structures at uniform rise of the dislocation density that provide for decrease of the local internal stresses to $(0.10–0.18)\tau_{theor}$ value.

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