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Crack Resistance of 14KhGN2MDAFB High-Strength Steel Joints Manufactured by Laser Welding

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Abstract. Today welded joints of high-strength steels, which are used in machine building and manufacture of structure, operating under difficult service conditions (static, dynamic, cyclic loads etc.) require a high level of mechanical properties of welded structures that mainly depend on a series of factors. Taking into account significant changes of technological modes in laser welding in comparison with traditional arc welding the investigation of structure change in welding zone and effect of these changes on service properties of welded joints is a relevant problem. The aim of the present work in investigation of effect of structure transformation and metal phase content on change of the most significant service properties of welded joints, namely indices of strength and crack resistance in zone of laser welding in butt joints of 14KhGN2MDAFB high strength steel. Structural-phase state and chemical elements composition in the weld metal and in the heat-affected zone were studied by optical microscopes, analytical scanning microscope, and transmission micro diffraction electron microscope. The dependencies of effect of laser welding speed on properties of welded joint of 14KhGN2MDAFB steel were determined. The most favorable structures (formation of fine grain lower bainite structures, absence of extended dislocation accumulations, uniform dislocation distribution) in the investigated joints is obtained at welding speed 13.9 mm/s. This mode guarantees their crack resistance.

Introduction

For a comparatively short period of time laser welding of structural materials has got a significant development [1-5]. It moved from precision pulse microwelding of electron components [6-8] to "power" penetration of high-strength steel of large thickness [3, 5, 9-11]. Together with development of commercial equipment [1, 4, 6, 11] and technologies of laser [1-8, 10] and different methods of hybrid welding [1, 5, 9, 11-14] there was created of scientific basics of this new direction. Different models of interaction of powerful laser radiation with a material were created [1, 6, 13, 14]; structure, mechanical, chemical and other effects in zone of welded joint were studied [1, 3, 5, 8 10]; fundamental principles of theory of different processes appearing at interaction of laser radiation with the materials were developed [1, 6, 9, 12-14].

Analysis of references [1-3, 5, 10, 15-17] shows that for the last 10 years there is a significant (5 times) increase of volumes of fundamental and applied scientific researches related with laser welding of high-strength steels. This resulted in growth of heat efficiency of modes, expansion of range of studied materials, types and thicknesses of welded joints, rise of percentage of implemented developments. Consequently joining of high-strength steel by laser radiation made a basis for formation of independent direction of modern welding engineering, and, thus, detection of the fields for technically and economically grounded application of laser welding under real conditions. This became a relevant task that is of considerable scientific and practical interest.

Today welded joints of high-strength steels, which are used in machine building and manufacture of structure operating under difficult service conditions [static, dynamic, cyclic loads etc.) [2, 5, 10, 15, 17-33] require a high level of mechanical properties of welded structures that mainly depend on a

series of factors [2, 18, 22, 25-31]. When selecting the welding methods it is necessary to take into account the peculiarities of welding modes as well as structure parameters forming at that in specific zones of the joint. This in many aspects determines a complex of service properties of welded joints, i.e. indices of strength, ductility and crack resistance [3, 5, 10, 17, 23, 25, 32]. Taking into account significant changes of technological modes in laser welding in comparison with traditional arc welding [5, 10, 17, 20, 24, 27-31] the investigation of structure change in welding zone and effect of these changes on service properties of welded joints is a relevant problem.

The aim of the present work in investigation of effect of structure transformation and metal phase content on change of the most significant service properties of welded joints, namely indices of strength and crack resistance in zone of laser welding in butt joints of 14KhGN2MDAFB high strength steel.

To solve these problems the examinations of changes of structure-phase state and density of dislocation in different zones of welded joints, received by laser welding on experimental modes, were carried out using the methods of optical metallography, scanning and transmission electron microscopy. Analytical estimations of a role of structure-phase constituents formed at different modes in change of the most significant service properties of welded joints, i.e. strength as well as crack resistance were made. They are caused by level of local internal stresses taking into account dislocation density distribution.

Materials for welded joints and their manufacture conditions.

The investigations were carried out on butt welded joints of high-strength 14KhGN2MDAFB steel (see Table 1) with plates thickness up to 10 mm.

Table 1

Chemical elements composition of 14KhGN2MDAFB steel

C	Cr	Mn	Ni	Mo	V	Si	P	S	Fe
0.183%	1.19%	0.98%	2.07%	0.22%	0.08%	0.33%	0.018%	0.005%	Bal.

Welded joints were manufactured at various speeds (5.0, 8.3, 13.9 mm/s) of laser welding using a technological CO_2-laser (wavelength of laser radiation is 10.6 μm, focal spot diameter of laser beam is 0.4 mm). No filler materials were use. In all modes, radiation power of the laser was 4.4 kW. Shielding gas flow rate of the mixture 18% CO_2 + 82% Ar was 233 cm^3/s.

Structural-phase state and chemical elements composition in the weld metal and in the heat-affected zone (HAZ) were studied optical metallography, analytical scanning electron microscopy (SEM), and transmission micro diffraction electron microscopy (TEM) as well (see Table 2).

Table 2

The equipment used in research

Microscopes	Specification	Brand	Country
Versamet-2	High Magnification Surface Microscope	Unitron	USA
Neophot-32	Optical Microscope	Karl Zeiss	Germany
SEM-515	Scanning Electron Microscope	Philips	Netherlands
JEM-200CX	High Performance Transmission Electron Microscope[*]	JEOL	Japan

* − Accelerating voltage of 200kV

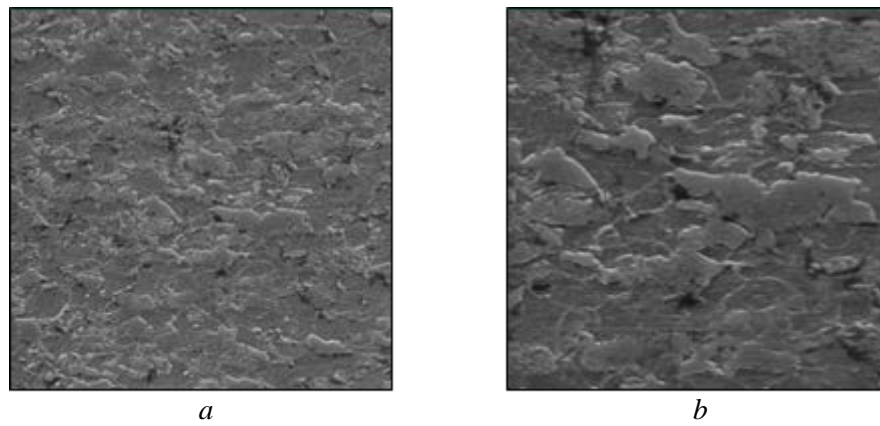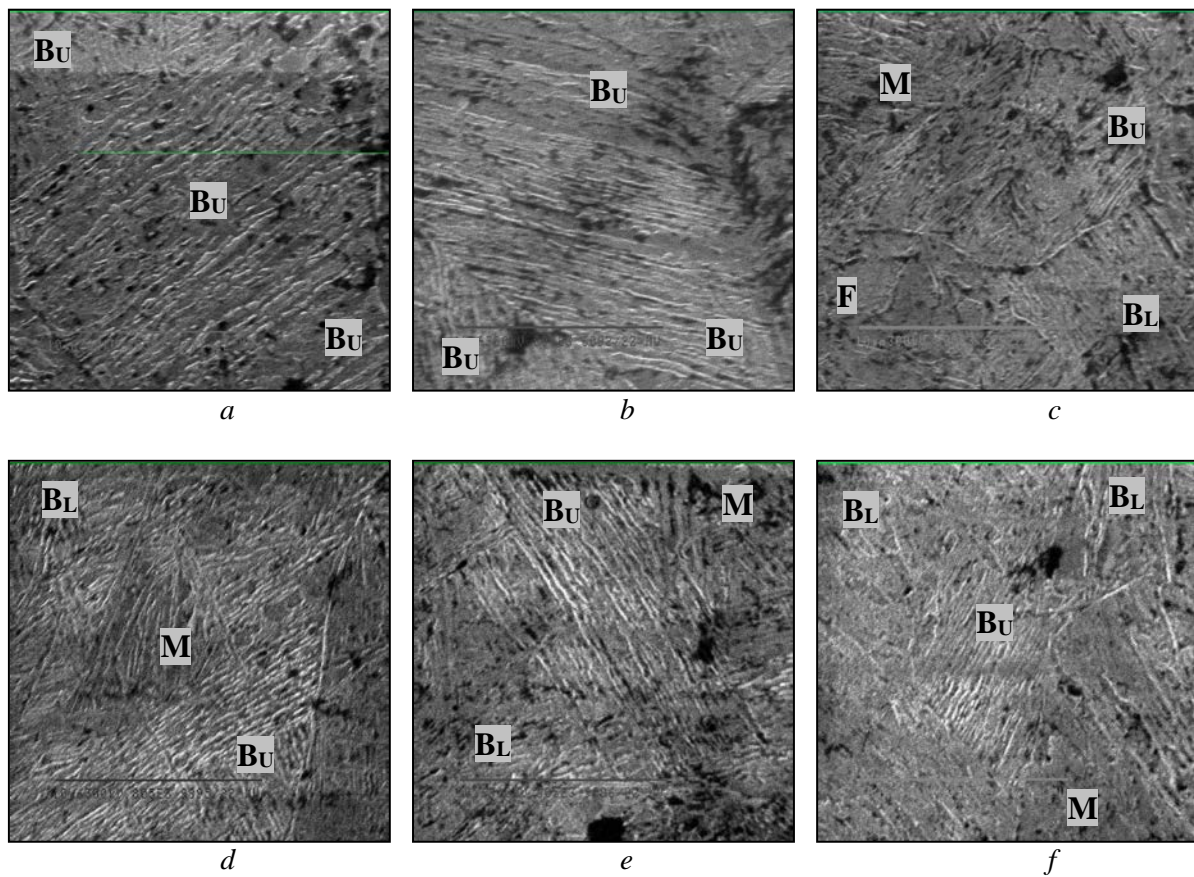Figure 1. Microstructure (SEM) of base metal: $a \times 4020$; $b \times 8050$;
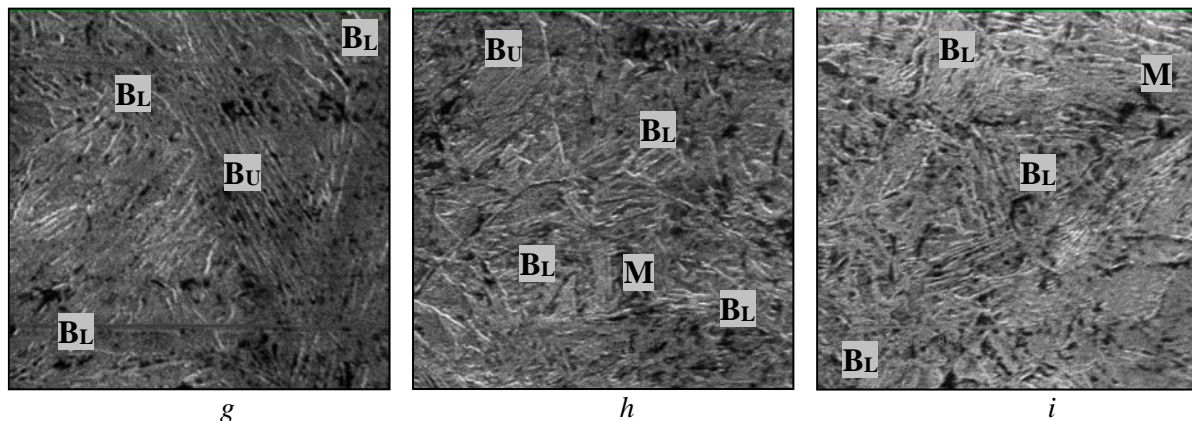
g   *h*   *i*

Figure 2. The microstructure (SEM) of the metal of welds (*a*, *d*, *g*) and the overheating area of HAZ (*b*, *c*, *e*, *f*, *h*, *i*) at laser welding: V_W = 5.0 mm/s (*a-c*); 8.3 mm/s (*d-f*) and 13.9 mm/s (*g-i*), ×8050.

The mechanical tests demonstrated that the temporary failure resistance σ_T (924...927 MPa) and the yield strength $\sigma_{0.2}$ (836...863 MPa) for the investigated modes (5.0...13.9 mm/s) of laser welding are approximately equal. The measure of impact bending of welded joints showed that at welding speed of V_W = 13.9 mm/s their toughness and cold resistance differ by an increase (in 1.4...1.6 times).

Results and Discussion

The studies of the structural-phase components such as bainite (B) in to modification lower bainite (B_L) and upper bainite (B_U), martensite (M), ferrite (F) formed in the weld metal and the HAZ and the corresponding changes in the microhardness, grain size D_G, shape factor have revealed the following. Structure of the base metal is B-F with grain size D_G = 5…24 μm and microhardness HV = 2740…2850 MPa, Fig. 1, *a*, *b*.

When laser welding was done on the minimum speed of 5 mm/s the weld metal structure was mostly B (grain size of 40...80×150...400 μm and a shape factor of 3...7, microhardness 2850…3510 MPa), Fig. 2, *a*. In the transfer from the weld to the HAZ the phase composition of the metal changes from B to B-M. In the HAZ the grain size reduces in 3...4 times (grain size of 50…90 μm) and microhardness increases by 17% (2850…3510 MPa), Fig. 2, *b*, *c*.

The B structure with a grain shape factor of 3...5 is typical for the metal of welded joints when the welding speed is 8 mm/s. It is characterized by gradients (1.2 times) by microhardness (3450…4010 MPa), which is due to the formation of B_U structure, Fig. 2, *d*. If we transfer from the weld to the HAZ, the phase composition of the metal changes from B to B-M, the microhardness (4010…4420 MPa) increases by an average of 12% when the grain structure is crushed in 3...4 times, Fig. 2, *e*, *f*.

When the welding speed is maximum (13.9 mm/s), the phase composition of the weld is B-M with a more equiaxed graininess structure at a grain shape factor of 2...3 and with no gradients of microhardness (3870…4330 MPa), Fig. 2, *g*. The phase composition of the weld metal and the overheating area of HAZ is the same (B-M) with the formation of mainly B_L structures and shredding of grain approximately in 3 times, Fig. 1, *h*, *i*.

Comprehensive TEM studies of the fine structure (the dislocation density in structural components, substructures in internal volumes of grains,etc.) have shown the following. In the weld metal and the overheating area of HAZ, at a welding speed of 5.0 mm/s, the width of laths of the B structures is h_l = 0.3...0.6 μm (in the weld, Fig. 2, *a*, *b*) and 0.2...0.5 μm (in the HAZ), respectively. Width of laths of the M structures of metal in weld zone is 0.5…1.0 μm. The microstructure of the weld metal and the metal of overheating area of the HAZ becomes more dispersed while common dislocation density increases by 1.8…2 times when the welding speed increases up to 13.9 mm/s. The width of laths of the B structures is reduced to 0.25...0.4 μm (in the weld) and 0.15...0.4 μm (in the HAZ), Fig. 2, *c*, *d*, *e* (d_S − subgrain size). It should be noted that the structure of tempered M is also formed [3].

For the case of minimum welding speed 5.0 mm/s dislocation density in welded joint metal makes $\rho = (2...4) \times 10^{10}$ cm^{-2} (in the weld) and $(4...6) \times 10^{10}$ cm^{-2} (overheating area of HAZ). However, there is formation of extended dislocation accumulations with $(1...1.2) \times 10^{11}$ cm^{-2} along grain boundary, mainly along B_U boundaries. This creates dislocation density gradient, Fig. 3, *b*. Increase of welding speed from 5.0 mm/s to 13.9 mm/s at total refinement of lath structure of B_L in the weld metal promotes relatively uniform distribution of dislocation volumetric density $(6...8) \times 10^{10}$ cm^{-2}, Fig. 3, *c*. For overheating area of HAZ its somewhat increase is typical (up to $(8...10) \times 10^{10}$ cm^{-2}), Fig. 3, *d*.
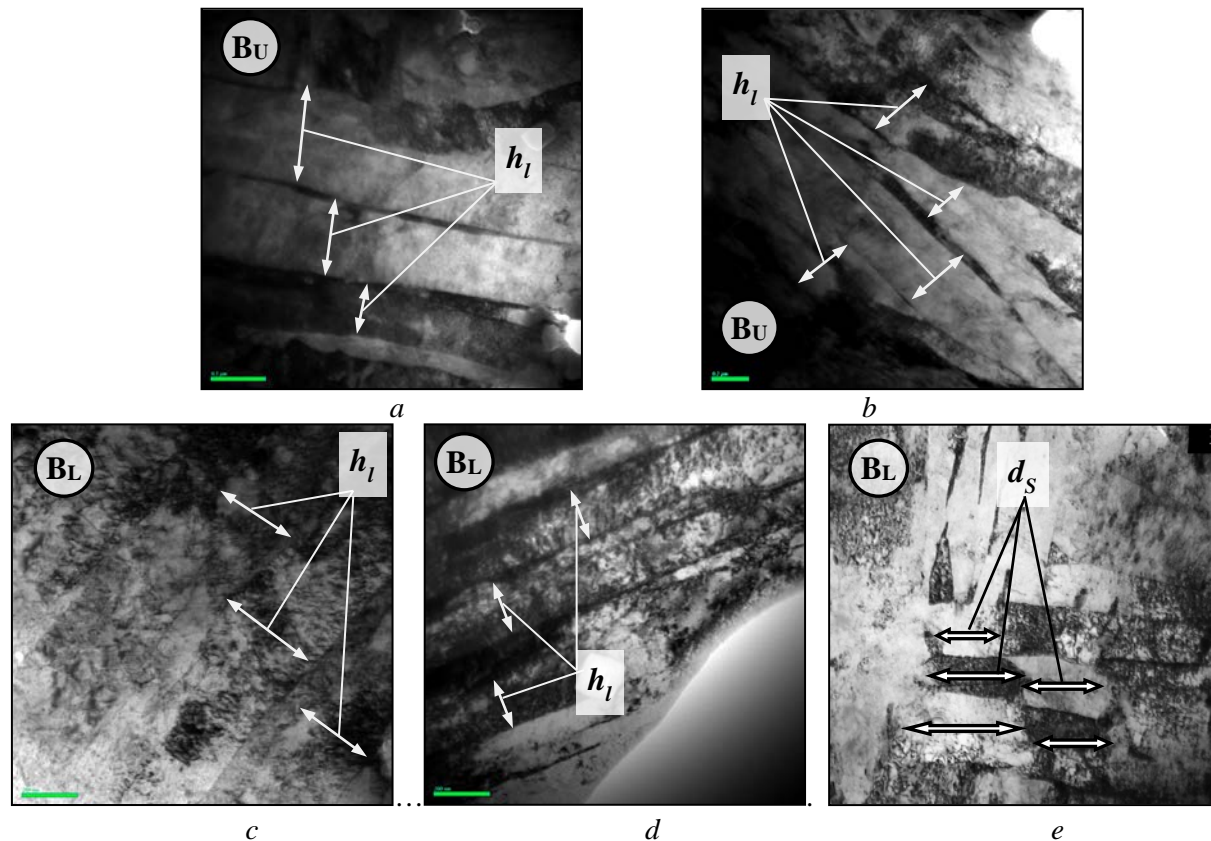

Figure 3. The fine structure (TEM) of the weld metal of welds (a, c) and the overheating area of HAZ (*b, d, e*) at laser welding: V_W = 5.0 mm/s (*a*×25000, *b*×35000); 13.9 mm/s (*c, d*×50000).

A comparison of the phase composition and microstructure of the weld metal in the studied welded joints showed that with an increase of the welding speed from 5.0 mm/s to 13.9 mm/s the phase composition of the weld metal changes from B to B-M. Microhardness increased by 25%. Crushing of the grain by 15% and reducing the grain shape factor from 3...7 to 2...3 forms more equiaxed grain structure. In B structure the laths width is reduced by 2 times. In overheating area of the HAZ, for all welding speeds, the phase composition of the metal is B-M. The microhardness stay approximately the same while the grains and the subgrains sizes are reduced in 1.5 times.

If we consider this from the point of view of uniform refinement of structural parameters, absence of gradients along the grain structure and microhardness, the most favorable structure of the studied welded joints is obtained at welding speed of 13.9 mm/s. Such speed provides and guarantees the uniform level of mechanical properties and crack resistance of welded joints [3].

Applying the experimental-analytical technique of estimation of strengthening.

Previously, we developed the technique of the experimental-analytical estimation of strengthening [3, 34]. A lot of the obtained experimental data allows us apple this technique for evaluate the

contribution of various structural parameters to the mechanical characteristics of welded joints of the high-strength steels. Like so we carried out the prediction of the properties of the strength of studied welded joints.

While we made analytical estimation of strengthening, the following components were considered:

o   the resistance of metal lattice to the movement of free dislocations (friction stress of lattice or Peierls-Nabarro stress) − $\Delta\sigma_0$;

o   the hardening of solid solution by alloying elements and impurities (solid solution hardening) − $\Delta\sigma_{S.S}$;

o   the hardening due to grain and sub-grain sizes (dependences of Hall-Petch, grain boundary and substructure hardening) − $\Delta\sigma_G$ and $\Delta\sigma_S$;

o   dislocation hardening due to dislocation interaction − $\Delta\sigma_d$;

o   dispersion hardening − the hardening due to dispersed particles according to Orowan − $\Delta\sigma_{d.h.}$:

$\Sigma\Delta\sigma_T = \Delta\sigma_0 + \Delta\sigma_{S.S} + \Delta\sigma_G + \Delta\sigma_S + \Delta\sigma_d + \Delta\sigma_{d.h.}$.

In the application of technique the experimental data were used that obtained by optical microscopy, SEM and TEM: grain size; the width of the laths of B structures; effective spacing between carbide phases, that is with taking into account the parameters of the fine structure − the dislocation density.

It have been revealed that if the speed of laser welding increases the strengthening effect of the structures increases. This is due to an increase in the contribution of the substructure hardening (1.8 times), dispersion hardening (2 times) and grain hardening (1.2 times) what was shown by comparison of the strengthening effect of the formed structures in the metal of the welded joints of 14KhGN2MDAFB steel.

So, we can predict quality of welded joints by the resulted techniques of quantitative estimation of strength properties of metal with concrete structural parameters. Moreover, when in a welding zone the microstructures of various type present we can reveal the structural factors rendering the basic influence on change of mechanical properties. We have shown that the coexistence of the fine-grained structure of B_L (Fig. 3, *c-e*) and tempered M will provide the highest parameters of hardening in metal of welded joints of 14KhGN2MDAFB steel (770...900 MPa).

The executed complex of experimental investigations at all the structural levels allowed carrying out analytical evaluations of the specific (differentiated) contribution of different structural and phase factors and parameters, formed in the investigated weld beads, in change of strength characteristics σ_T and determining the structural factors cardinal influencing on the character and distribution of local inner stresses ($\tau_{L/IS}$), which are the potential sources of nucleation and propagation of cracks in the investigated structural microregions [34].
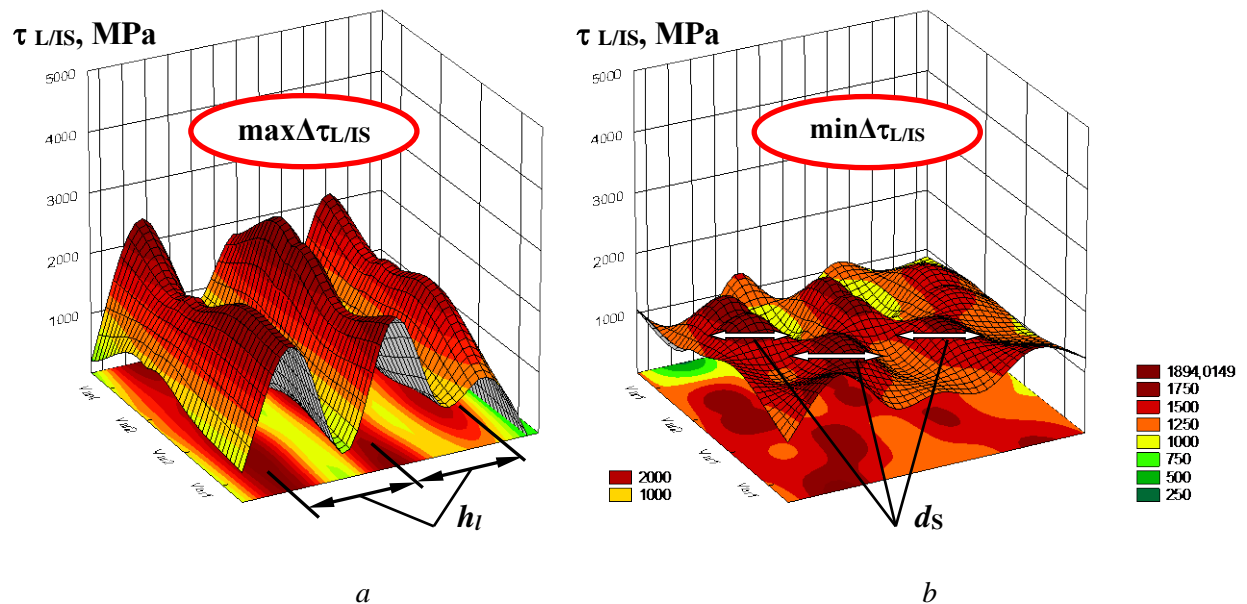
Figure 4. Local internal stress distribution ($\tau_{L/IS}$) in the metal welds in structural zones in the upper bainite (B_U) at welding speed 5.0 mm/s, (*a*) and lower bainite (B_L) at the welding speed 13.9 mm/s (*b*).

From the analysis of different approaches to determination of mechanisms of incipience of cracks and fracture of materials the evaluation of $\tau_{L/IS}$ was chosen basing namely on the dislocation theory of crystalline solid bodies, connecting the processes of formation of local inner stresses with initiation and rearrangement of dislocation structure [35-37]. The field of inner stresses, formed by the dislocation structure (dislocation density) and peculiarities of local inner stresses $\tau_{L/IS}$ – the sources of incipience and propagation of cracks (their level, length, interaction with structural features of weld beads), were determined by the dependence of:

$\tau_{L/IS} = G \cdot b \cdot h \cdot \rho / [\pi \cdot (1 - \nu)]$,

here b is the Burgers vector; G is the shear modulus; h is the foil thickness, equal to 2×10^{-5} cm; ν is the Poisson's ratio; ρ is the dislocation density.

Calculation estimations of local internal stresses ($\tau_{L/IS}$) given on diagrams of Fig.4 show the following. The maximum values of $\tau_{L/IS}$ = 1900...2280 MPa (Fig. 4, *a*) are formed in a metal of overheating area of HAZ (5.0 mm/s) in places of extended dislocation accumulations $(1...1.2) \times 10^{11}$ cm^{-2} along the boundaries of B_U lathes, Fig. 3, *a*, *b*. This results in nucleation of microcracks in these zones and decrease of crack-resistance in welded joints. The lowest values are observed at comparatively uniform their distribution and make $\tau_{L/IS}$ = 1470...1660 MPa (13.9 mm/s, рис. 4, *b*), that is assisted by formation of fine grain structures of B_L, Fig. 3, *c*, *d*, *e*.

Conclusions

1. The dependencies of effect of laser welding speed on properties of welded joint of 14KhGN2MDAFB steel were determined.
2. Increase of welding speed from 5.0 mm/s to 13.9 mm/s changes phase composition of weld metal and heat affected zone from bainite to bainite-martensite, ratio of forming phase constituents (lower bainite, upper bainite and martensite), their parameters and volume fraction as well as rises microhardness; decreases size of grain an subgrain bainite structure.
3. Upper bainite structures are mainly formed in welded joint metal at minimum speed (5.0 mm/s) of laser welding with non-uniform and gradient dislocation of dislocation density that result in decrease of welded joint crack resistance.

4. The most favorable structure (formation of fine grain lower bainite structures, absence of extended dislocation accumulations, uniform dislocation distribution) in the investigated joints is formed at welding speed 13.9 mm/s. This mode guarantees their crack resistance.

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