MICROSTRUCTURAL FEATURES OF FATIGUE DAMAGEABILITY AND METHODS TO IMPROVE THE FATIGUE LIFE OF WELDED JOINTS FROM 09G2S STEEL

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The paper presents the results of investigation of the effect of cyclic bend loading on brittle fracture resistance of the HAZ metal, as well as accumulation of fatigue damages and structural changes in butt and T-welded joints in 09G2S steel. It is shown that presence of a sharp stress raiser at low temperatures (−40 °C and lower) leads to lowering of brittle fracture resistance of HAZ metal of welded joints with fatigue damages.

Keywords: *arc welding, low-alloyed steel, welded joints, brittle fracture resistance, fatigue damage, microstructure, fatigue life*

One of the main causes of failures and breakage of machines, mechanisms and engineering constructions is fatigue of structural materials in individual most loaded item components. These most often are weldments which have design or structural stress raisers. Despite the great success in studying the fatigue features and availability of various techniques to improve the fatigue life of welded metal structures, the number of accidents caused by fatigue is still considerable. In this connection, the results of investigations in fatigue area and, particularly, of fatigue damageability of structures are of great interest.

It should be noted that the majority of researchers are studying fatigue phenomena in metals and predominantly the dislocation structure both within the stable slip bands, and in the matrix using electronic microscopy [1]. Over the recent years research aimed at finding the possibility to predict the degree of fatigue damage of structural elements or equipment has been intensively pursued. Prediction of the time of safe operation of various structures and equipment should be based on investigation of metal fatigue features on the microlevel [2]. Without detailed investigations of processes occurring in these metal layers, it is difficult and sometimes impossible to give a well-substantiated statement about the extent of fatigue damageability development in the item at cyclic loading. Technical publications contain practically no information that would allow evaluation of the influence of structural changes, which occur as a result of fatigue phenomena, on mechanical properties of high-strength steel welded joints.

A basic point at definition of the research problem in this work was the fact that at present the number of loading cycles preventing fracture is considered as a function of cyclic deformations [2, 3] or stresses [4], causing fatigue damage accumulation. Accordingly, a distinction is made between two fatigue periods — incubation, in which fatigue damage accumulation occurs, and active, in which fatigue crack initiation and propagation occur.

In this work the influence of microstructural features of fatigue damageability under cyclic loading and manifestations of plastic deformation, formation of fatigue cracks, as well as the influence of cyclic loading of metal of HAZ of welded joints on their brittle fracture fatigue resistance at subsequent static loading of standard specimens, cut out of tee samples after cyclic loading, was studied in order to determine the critical stress intensity factor K_{IC} and critical crack opening displacement δ_c, depending on the number of cycles of tee joint loading.

Butt joints (B25) and tee joints with a stiffener from 09G2S steel of 30 and 10 mm thickness, respectively, transverse relative to the action of the forces (T8 to GOST 14771–76), were selected as the object of study. They were made by mechanized welding process with solid wire Sv-08G2S of 1.2 mm diameter in CO_2. Composition and mechanical properties of steels, as well as those of metal deposited with the above consumable, are given in Tables 1 and 2.

At the first stage of investigations samples 120 mm wide and 480 mm long were cut out of the welded joints, which were then subjected to symmetrical cyclic loading by bending at 14 Hz frequency. It is established that fatigue cracks more than 2 mm long in butt welded joints, which were tested at cycle stress σ_a = 100 and 130 MPa, formed after 200,000 and 110,000 cycles, respectively ($N = N_{Fr}$, where N is the number of loading cycles; N_{Fr} is the number of loading cycles, at which fatigue cracks form), and in tee welded joints, which were tested at cycle stress of 80 and 120 MPa, they were revealed after 880,000 and 490,000 cycles, respectively.

Table 1. Composition (wt.%) of 09G2S steel and metal deposited with Sv-08G2S wire

Material	C	Mn	Si	S	P
09G2S steel	0.10	0.71	0.57	0.024	0.021
Deposited metal	0.08	1.30	0.80	0.017	0.019

Table 2. Mechanical properties of 09G2S steel and metal deposited with Sv-08G2S wire

Material	σ_y, MPa	σ_t, MPa	δ_5, %	ψ, %	*KCV*, J/cm^2, at T_{test}, °C		
					+20	−20	−40
09G2S steel	367	553	28	68	150	120	64
Deposited metal	375	508	23	66	145	65	15

At the second stage welded joints in as-welded condition, as well as after cyclic loading at achievement of N = 0.45, 0.70 and 0.80 of N_{Fr}, were used to prepare standard specimens of 15 × 30 × 145 mm (butt joint) and 10 × 20 × 100 mm size (tee joint) for assessment of test results using fracture mechanics criteria. Specimens were cut out so that the tips of fatigue cracks, which initiate at the notch tip, were located only in the zone of localizing of metal plastic deformation. Such a region in welded joints is the line of weld fusion with base metal, where the natural stress raiser is located, which is due to weld geometry. Results of specimen testing for three-point static bending, conducted at the temperature from +20 up to −40 °C, are shown in Figure 1.

Results of testing specimens made from butt joints showed that at temperature from +20 to −20 °C, there are no noticeable changes in brittle fracture resistance of HAZ metal of 09G2S steel welded joints (Figure 1, *a*, *b*). Lowering of K_{IC} and δ_c values was observed at T_{test} = −40 °C in the case, when $N/N_{Fr} \geq$ 0.7. Similar regularities of decrease of K_{IC} and δ_c values in the HAZ metal of welded joints, cyclic loading of which was interrupted at the stage preceding fatigue crack formation, were found also at testing specimens cut out of tee joints of 09G2S steel (see Figure 1, *c*, *d*). This is, obviously, related to the fact that during cyclic loading an essential accumulation of fatigue damage occurs in individual microvolumes, and ductile properties of metal are exhausted, as a result of which it loses its ability to effectively resist brittle fracture.

Investigation of the process of fatigue damage accumulation and features of microstructure changing under the impact of cyclic loading were performed on specimens cut out of butt and tee welded joints of 09G2S steel, which were loaded by different number of cycles. They were used to make microsections which were etched in 4 % HNO_3 solution in ethyl alcohol. After multiple periodical repolishing and etching of the surface, microstructure of microsections was studied in «Neophot-34» microscope, Philips scanning electron microscope SEM-515 and LECO microhardness meter M-40 under varying loads. X-ray structure analysis was performed in DRON-UM-1 diffractometer in monochromatic CuK_α-radiation by the method of step scanning. Graphite single crystal was used as the monochromator.

As shown by investigations, in metal of all types of welded joints subjected to cyclic deformation, indications of fatigue phenomena were found in the form of fatigue damage (stable slip bands, extrusion and intrusion) and fatigue changes of microstructure (Figures 2 and 3). They appeared after a certain number of deformation cycles, which was different for different types of specimens.

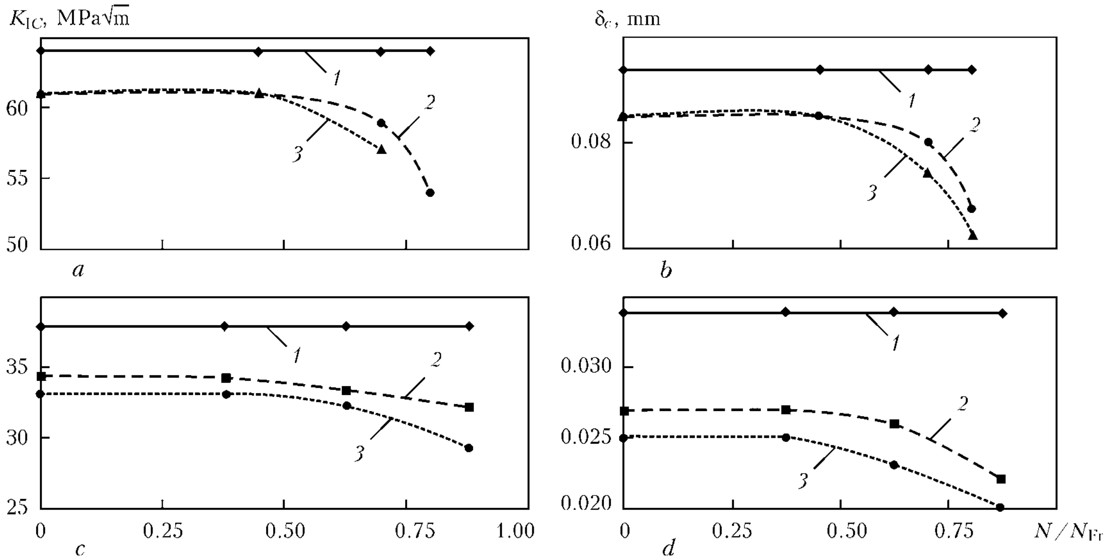


Figure 1. Change of K_{IC} (*a*, *c*) and δ_c (*b*, *d*) values of HAZ metal of butt (*a*, *b*) and tee (*c*, *d*) welded joints of 09G2S steel with increase of the number of deformation cycles (cycle stresses for butt joints were 100 (*a*), 130 (*b*) MPa, and for tee joints — 80 (*c*), 120 (*d*) MPa): *1* — T_{test} = +20 and −20 °C; *2*, *3* — T_{test} = −40 °C

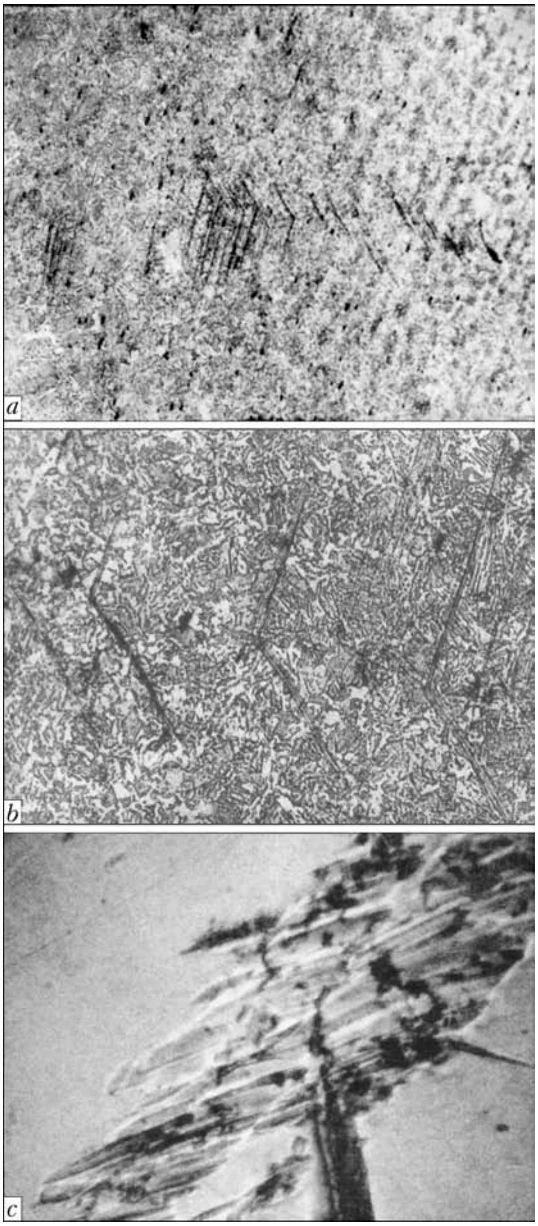


Figure 2. Slip bands, extrusions, intrusions in the metal of samples of 09G2S tee joints: *a*, *b* — N = 230,000 cycles, σ_a = 120 MPa; *c* — N = 720,000 cycles, σ_a = 80 MPa (*a* — ×100; *b* — ×500; *c* — ×1000)

The most numerous of the detected fatigue damages in 09G2S steel welded joints both butt and tee, were stable slip bands, which did not disappear even after multiple repolishing of the specimens. Irrespective of the types of welded joint, the number of slip bands rises with increase of the number of loading cycles, and the bands proper are a family of slip lines.

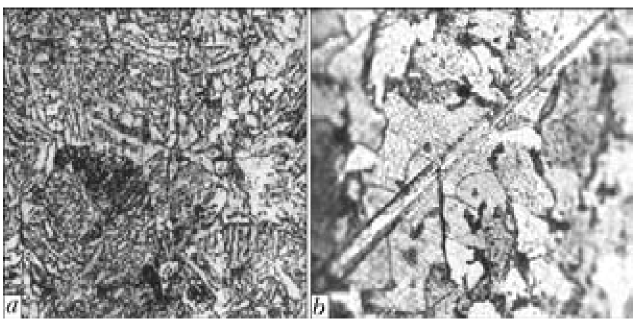


Figure 3. Fatigue changes of microstructure of HAZ metal of 09G2S steel butt welded joints: *a* — N = 230,000 cycles, σ_a = 120 MPa; *b* — N = 720,000 cycles, σ_a = 80 MPa (*a* — ×500; *b* — ×1000)

Considering that stable slip bands are located in slip planes and their orientation, as a rule, coincides with the direction of transverse sliding of dislocations [5, 6], it can be assumed that stable slip bands arose in those grains, where a certain dislocation density and critical stress level were achieved. As is known, after achievement of a critical stress level, dislocation movement starts in the direction close to their slip plane (transverse sliding of dislocations). Here critical stress depends primarily on the level of substructure development, and is inversely proportional to it. This accounts for the fact that in the HAZ metal, and, in particular, in the overheated region of the studied welded joints, slip bands formed more frequently than in the base metal. This is related to the fact that austenite transformation in this region during welding occurred by the shear diffusionless mechanism, unlike those regions of HAZ and base metal, where its transformation proceeded by the diffusion mechanism or did not occur at all. It should be noted that detection of stable slip bands in HAZ metal was difficult, because of the presence of a multitude of second phases in the structure.

Second phases obscure fatigue phenomena in the microstructure to an even greater extent, so that the latter are difficult to detect. As is seen from Figure 4, the main structural component of overheated zone of HAZ metal in butt and tee joints in the initial (as-welded) condition is bainite of globular (microhardness $HV50$ = 1880–2120 MPa) and plate-like morphology ($HV50$ = 2200–2430 MPa). Grain-boundary (hypoeutectoid) and seldom acicular ferrite are also present in the structure.

It is known [1] that depending on the initial structural state of material and cyclic loading conditions, material resistance to cyclic deformation can rise (and, therefore, material is strengthened), decrease or remain unchanged with increase of the number of loading cycles. In material softening zone such surface damage as extrusion and intrusion [2] develops, which is a consequence of material fatigue [2, 3].

In this work microhardness measurement was used to study the reaction of HAZ and base metal on cyclic deformation, depending on the number of loading cycles. Results of these investigations, given in Figure 5, are indicative of the fact that during cyclic loading of welded joints of 09G2S steel both strengthening and softening of HAZ metal and adjacent base metal regions take place. Strengthened and softened regions are of a local nature and alternate.

It is established that under the impact of cyclic deformation, fatigue changes (see Figure 3) occur in the HAZ metal structure of 09G2S steel welded joints, which consist in the change of the nature of dislocation

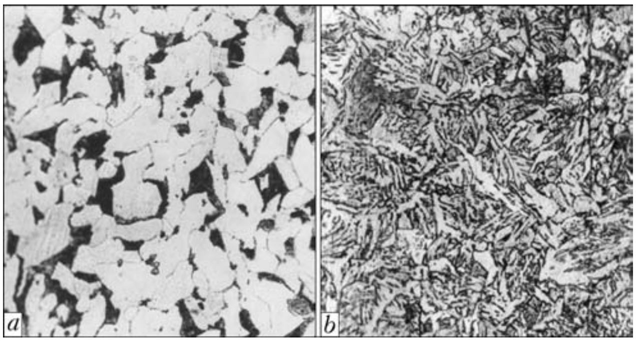


Figure 4. Microstructures (×500) of 09G2S steel (*a*) and HAZ metal (*b*) of tee welded joints

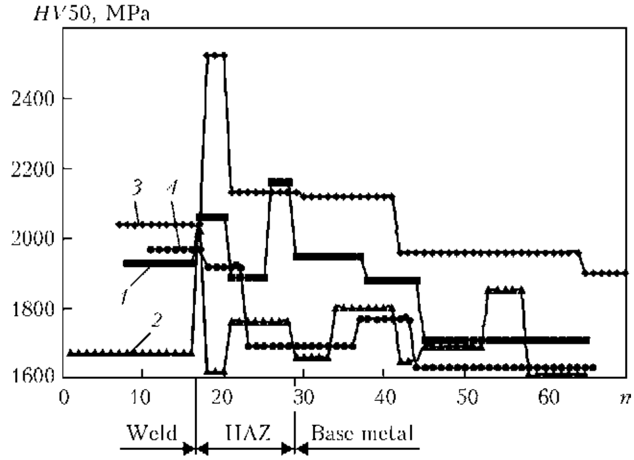


Figure 5. Microhardness of samples of tee welded joints of 09G2S steel after welding (*1*) and cyclic loading σ_a = 80 MPa up to N = = 400,000 (*2*), 700,000 (*3*) and 100,000 (*4*) cycles: n — number of measurements

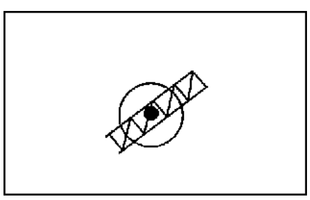
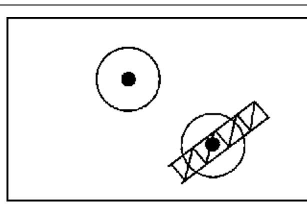
distribution, namely in their redistribution with formation of band structures. Degree of development of fatigue changes in the microstructure is different in different microvolumes, and, apparently, depends on their crystallographic sensitivity to the direction of load application axis, local stress concentration, as well as concentrational inhomogeneity as to impurity and alloying elements.

Alongside the stable slip bands, extrusions, intrusions and fatigue changes of the microstructure, transverse microshears were found on the surface of samples of tee joints subjected to cyclic deformation in different loading modes (Figure 6). The fact that under the same conditions of cyclic loading transverse microshears occur in samples of tee welded joints and are absent in butt joint samples, is, apparently, attributable to the initially higher rigidity of tee joints. A microshear, could, most probably, be initiated by dislocation clusters near the grain boundaries, carbide inclusions or second phase globules, as well as cleavages of non-metallic inclusions inside the grains.

In this work a specimen of 9 × 12 mm size was studied, which was cut out of cyclically deformed tee joint (σ_a = 80 MPa and N = 720,000 cycles, which is equal to $0.8N_{\mathrm{Fr}}$), on the surface of which a region with a transverse microshear was found. Diffractometric studies of the specimens were performed using X-ray structural analysis. D_{HKL} value of blocks of regions, where microstructural changes and microstresses $\Delta a/a$, accompanying these changes, occur, was assessed. With this purpose two measurement points were selected: a — in the center of transverse shear; b — ahead of transverse shear. Time of exposure in the point was 40 s, and measurement step was 0.05°. Results of diffractometric studies given in Table 3 are indicative of the fact that microstress relaxation occurs in the region of transverse microshear. This is logical, because, as follows from references [1–3], the microshear, which is realized through atomic bond rupture under the impact of external stress, is the initial stage of submicrocrack growth. Rupture of such bonds occurs in the plane with the lowest atomic packing density, having the lowest values of surface energy. For metals with bcc lattice this is plane {100}.

As fatigue changes in welded joints occur in their local and quite definite zones, further studies were aimed at finding technological methods to improve the fatigue life of such joints and recovering their ability to resist brittle fracture. Effect of preventive repair by welding was studied, which is performed at the stage, preceding fatigue crack formation, and

Table 3. Results of diffractometric studies

Measurement points	Measurement schematic	D_{HKL}, nm	$\Delta a/a\cdot10^{-4}$
a		$\to 0$	$\to -\infty$
b		48.61	6.188

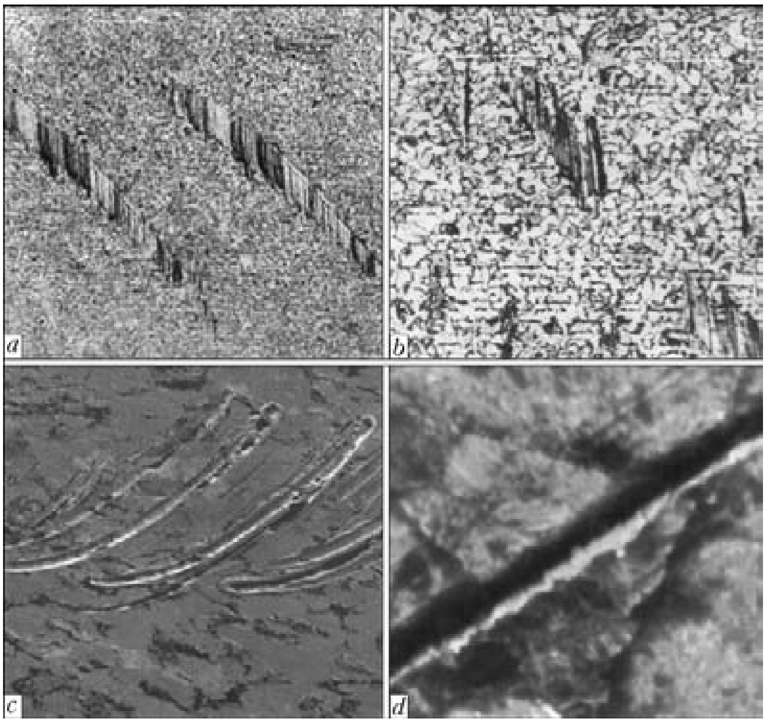


Figure 6. Microstructures with transverse microshears in samples of tee joints of 09G2S steel: *a* — σ_a = 120 MPa, N = 400,000 cycles; *b*–*d* — σ_a = 80 MPa, N = 720,000 cycles (*a* — ×50; *b* — ×125; *c* — ×810; *d* — ×5000)

which consists in deposition of additional beads along the edges of existing welds, as well as various kinds of metal strengthening (high-frequency mechanical peening, shock-wave or electric pulse treatment).

These investigations were performed by the limited fatigue life method for specimens cut out of tee joints of 09G2S steel 10 mm thick. After welding the samples were subjected to cyclic loading up to 400,000 cycles ($0.8N_{\rm Fr}$) at cycle stress of 120 MPa. Then, they were repaired by welding or strengthened by various technologies, and then again subjected to cyclic loading at the above mentioned load up to formation of 2 mm fatigue crack. Other repaired or strengthened welded joints were used to make standard samples (type 11 to GOST 9454–78) for impact bend testing, which was conducted at $T_{\rm test}$ = –40 °C.

Investigation results showed that after preventive repair by welding and high-frequency mechanical peening of welded joints their fatigue life rises 2–2.2 times. Fatigue life of welded joints after electric-pulse and shock-wave treatment increases somewhat less (1.4–1.8 and 1.4–1.5 times).

Impact bend testing showed that in as-welded condition impact toughness KCV_{-40} of HAZ metal of 09G2S steel welded joints is equal to 10.0–13.1 J/cm^2, and as a result of cyclic loading it decreases to 6.8–8.2 J/cm^2. After preventive repair using welding and strengthening treatments KCV_{-40} value rises but to different extent. In welded joints after preventive repair by welding impact toughness practically on the level of the initial condition (KCV_{-40} = 10.1–10.8 J/cm^2) was recorded. It rose up to 9.2–10.2 and 8.9–9.6 J/cm^2 after high-frequency mechanical peening and shock-wave treatment. Electric-pulse treatment did not have any essential influence on impact toughness of HAZ metal of 09G2S steel welded joint.

CONCLUSIONS

1. At cyclic loading by bending ($N/N_{\rm Fr} \geq 0.7$), accumulation of fatigue damage takes place in HAZ metal of 09G2S steel welded joints: stable slip bands, extrusions and intrusions form, their number increasing together with increase of loading cycle number.

2. Fatigue damages accumulated in HAZ metal of 09G2S steel facilitate its embrittlement and, as a result, lead to lowering of cold resistance by 20–40 %.

3. Fatigue life of 09G2S welded joints can be effectively increased 1.8–2.2 times and HAZ metal cold resistance can be restored to the initial condition through application of preventive repair performed at the stage preceding formation of fatigue cracks, by deposition of additional beads along weld edges and (or) performance of high-strength mechanical peening of the zone of weld-to-base metal transition.

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