IMPROVEMENT OF FATIGUE RESISTANCE OF WELDED JOINTS WITH ACCUMULATED DAMAGE UNDER MULTISTAGE AND BLOCK LOADING

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The paper gives results of fatigue tests of tee welded joints on steel 09G2S strengthened by the technology of high-frequency mechanical peening after accumulation of 50 % of fatigue damage under the impact of multistage and block loading with differing parameters before and after strengthening. It is established that utilisation of this technology allows increasing the level of stresses initially applied to such joints and extending their residual fatigue life.

Keywords: *accumulation of fatigue damage, high-frequency mechanical peening, cyclic fatigue life, fatigue, welded joint*

Engineering structures are usually affected during operation by complex loading conditions, where the sequence of values of amplitudes and average stresses in a cycle changes in a random way [1]. Studies [2–4] give data of experimental investigations on using high-frequency mechanical peening (HFMP) to increase load-carrying capacity of welded elements of the operating metal structures, which are strengthened after accumulation of a specified level of fatigue damage to initiation of crack. It is shown that after strengthening of the joints by the HFMP technology the levels of service loads can be substantially increased together with ensuring the specified fatigue life. Investigations in this area were carried out only under regular loading. In this connection, proving the efficiency of strengthening of the welded joints in structural elements by the HFMP technology in order to increase the load-carrying capacity of the operating structures under the effect of irregular loading is a task of current importance.

The purpose of this study was to experimentally prove the efficiency of using the HFMP technology for strengthening of tee welded joints in operating metal structures to increase their load-carrying capacity under conditions of different-parameters multistage and block loading before and after peening.

Experimental investigations were carried out with specimens of the T-joints on steel 09G2S (σ_y = = 370 MPa, σ_t = 540 MPa). Billets for the specimens of this steel were cut out from rolled plates, so that the long side was oriented along rolling. Transverse stiffeners were joined by the fillet welds on both sides by manual arc welding using electrodes UONI-13/55. The shape and geometrical sizes of a specimen are shown in Figure 1. The given thickness of the specimen was due to a wide application of the 12 mm thick rolled plates in welded structures, and width of the gauge part of the specimen was chosen on the basis of capacity of the testing equipment. In strengthening of the joints by the HFMP technology the narrow weld to base metal transition zone was subjected to plastic surface deformation. Fatigue tests of the specimens were carried out by using testing machine URS 20 with uniaxial alternating tension at cycle asymmetry $R_\sigma = 0$. All specimens were tested to complete fracture.

The efficiency of using the HFMP technology to improve fatigue resistance characteristics of the welded joints with accumulated fatigue damage under the effect of different multistage and block loadings before and after strengthening was evaluated by comparing the experimental data of fatigue tests of the welded joints in the as-welded state and strengthened after the specified quantity of alternating loading cycles. The experimental data of tests of the investigated welded joints in the as-welded state under multistage and block loading were generated earlier in studies [5, 6].

Fatigue tests of the T-joints on steel 09G2S strengthened after the specified quantity of cycles of alternating stresses were carried out on 18 specimens,

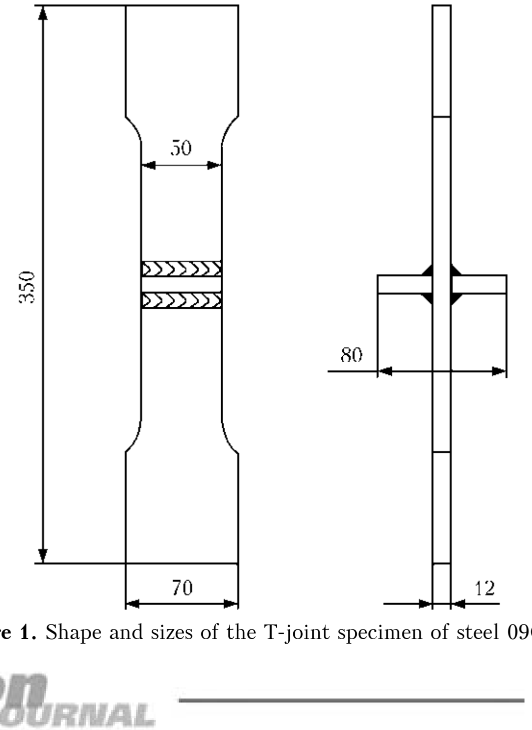

Figure 1. Shape and sizes of the T-joint specimen of steel 09G2S

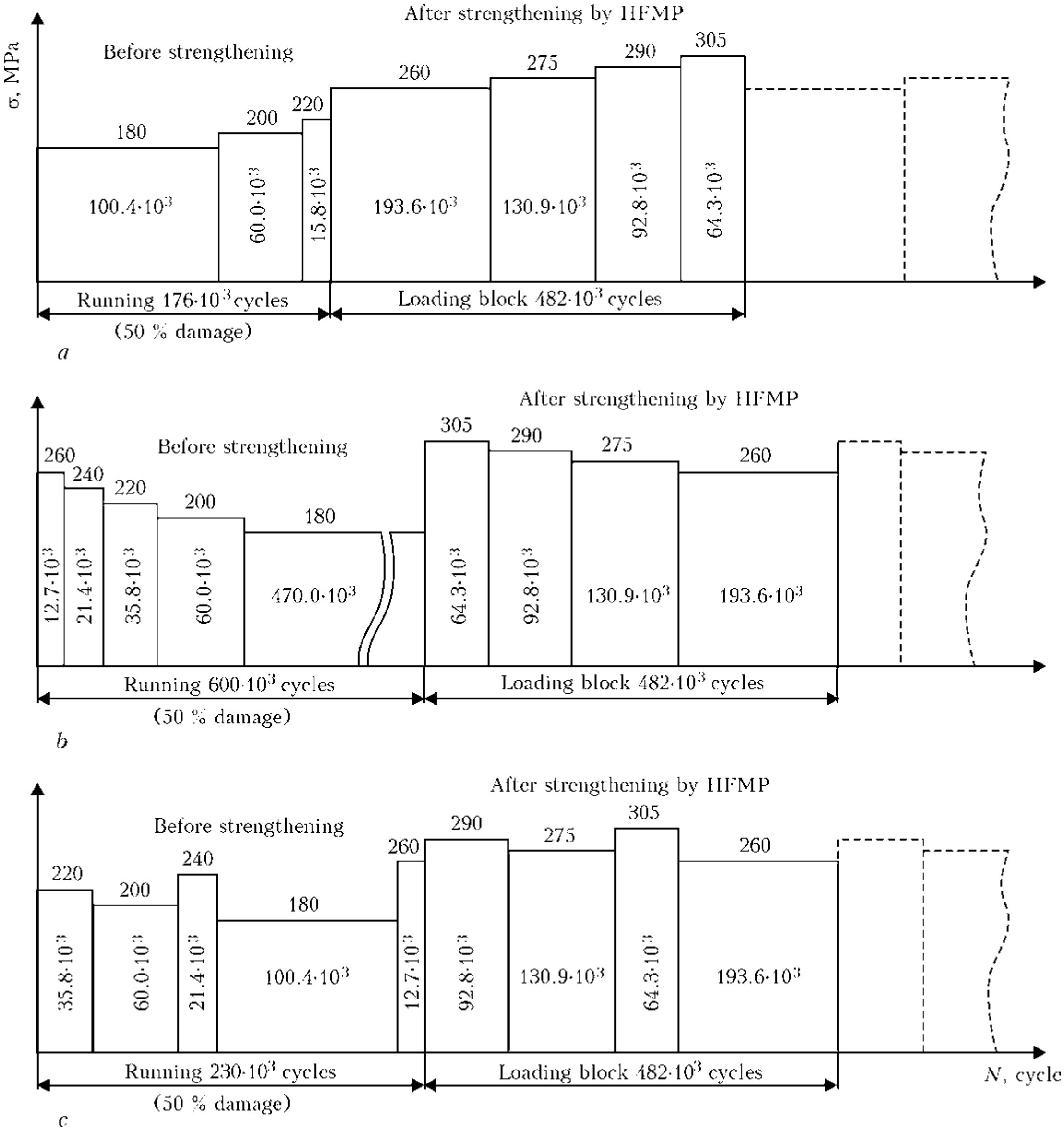

Figure 2. Diagram of loading of the T-joint specimens of steel 09G2S before and after strengthening under multistage loading with increasing (*a*), decreasing (*b*) and quasi-random (*c*) sequences of application of load

9 specimens under each multistage and block loading, respectively, with increasing, decreasing and quasi-random sequences of application of load in a block. Three specimens were tested with each sequence of application of load under the conditions of multistage loading, and three specimens — under the conditions of block loading.

With multistage and block loading of the joints in the as-welded state the sequence of application of load was set by the similar five levels (stages) of the applied maximal stresses in a cycle, but with a different degree of accumulation of damage (quantity of stress alternation cycles) at each level. The increasing sequence of application of load in a block was set by the initial maximal stresses in a cycle equal to 180 MPa at the first stage of loading with their subsequent increase to 260 MPa (the fifth stage of loading) at a pitch of 20 MPa. The decreasing sequence of application of load in a block was set by the initial level of maximal stresses in a cycle equal to 260 MPa with their subsequent decrease to 180 MPa also at a pitch of 20 MPa. The quasi-random sequence of application of load in a block was set by another five sequential levels of maximal cycle stresses in a block: 220, 200, 240, 180 and 260 MPa.

Strengthening of the welded joints by the HFMP technology was carried out after the joints had accumulated 50 % fatigue damage. The quantity of stress alternation cycles before strengthening at each loading stage under the conditions of multistage and block loading was set proceeding from the earlier established ultimate values of the sum of relative fatigue lives (fracture criteria) for the tee welded joints on steel 09G2S in the as-welded state under similar loadings [5, 6]. Under multistage alternating loading, for all sequences of application of loads the total damage of the joints equal to 50 % was set by decreasing two times the values of the running cycles, given in study

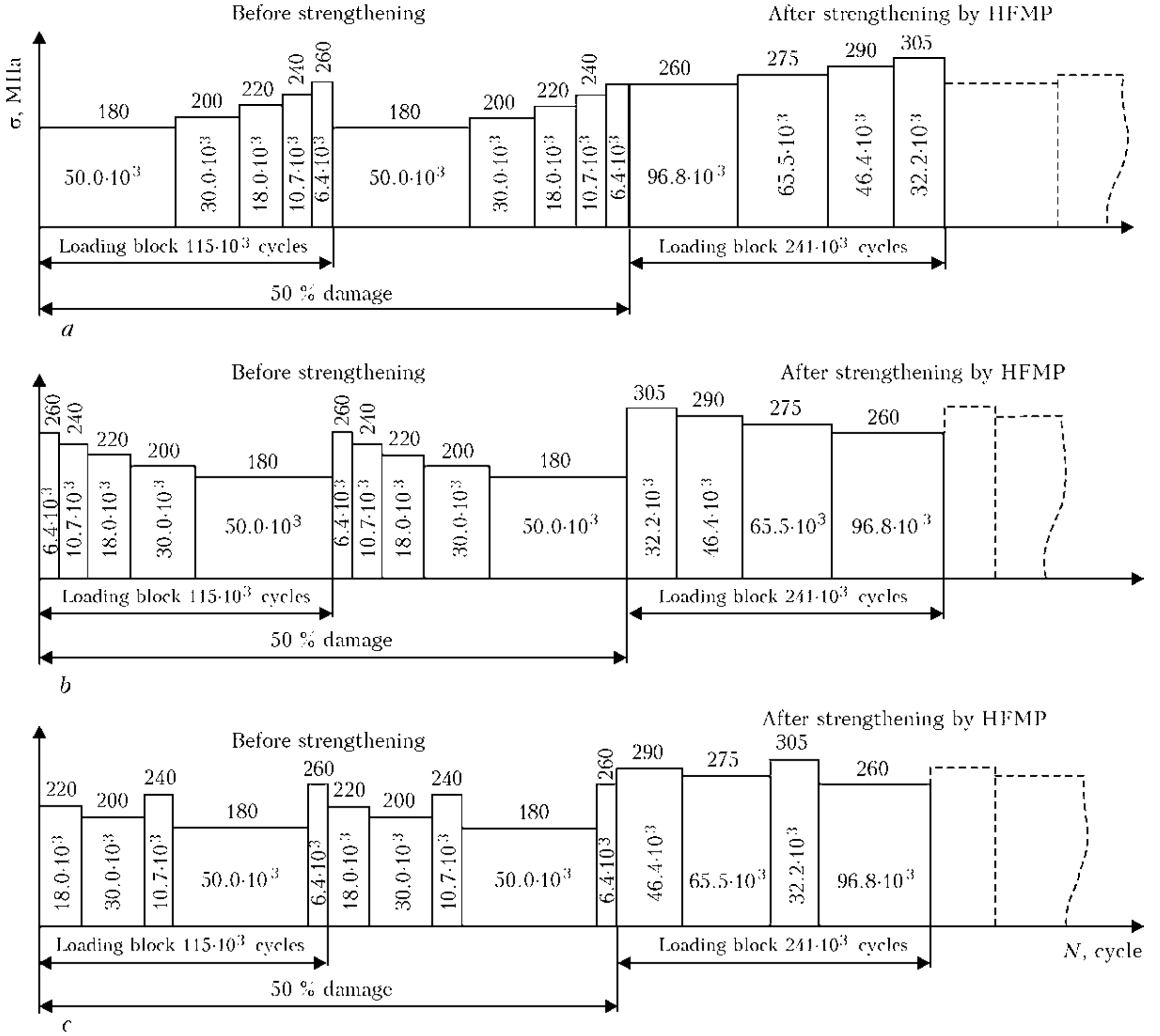

Figure 3. Diagram of loading of the T-joint specimens of steel 09G2S before and after strengthening in block loading with increasing (a), decreasing (b) and quasi-random (c) sequences of application of load in each block

[5], at each stage of loading to fracture of the specimens (Figure 2). The growing sequence of application of load was set by three loading stages, and the decreasing and quasi-random ones — by five loading stages. Under block loading, for all sequences of application of load in a block the total damage of the joints equal to 50 % was set by decreasing 2 times the quantity of the loading blocks to fracture of the welded specimens, compared to that given in study [6], the quantity of cycles in a block being left unchanged (Figure 3). All sequences of application of loads under block loading were set by five loading stages.

After strengthening by the HFMP technology, the sequence of application of load in a block (increasing, decreasing and quasi-random) under the multistage and block loading conditions remained unchanged. The loading block proper was set now not by five loading stages, as before strengthening, but by four stages increased with respect to the initial ones. The increased levels of the applied maximal stresses in a cycle corresponded to the levels of fatigue limits of the strengthened joints (because of HFMP the fatigue limit of the welded joints under consideration grew by 56 %, and the fatigue life increased up to 10 times) [5].

After HFMP strengthening of the tee welded joints with 50 % damage the increasing sequence of application of load in a block was set by the maximal stresses in a cycle equal to 260 MPa at the first loading stage with their subsequent increase to 305 MPa (the fourth loading stage) at a pitch of 15 MPa. The decreasing sequence of application of load in a block was set by the initial level of the maximal stresses in a cycle equal to 305 MPa with their subsequent decrease to 260 MPa also at a pitch of 15 MPa. The quasi-random sequence of application of load in a block was set by the following four sequential levels of the maximal cycle stresses in a block: 290, 275, 305 and 260 MPa. The quantity of the stress alternation cycles at each stage of loading of a specimen under the multistage loading conditions corresponded to 12.5 %, and that under the block loading conditions — to 6.25 % of fatigue life of the specimen strengthened in the as-welded state [5]. This approach provided the total damage per four loading stages (loading block) under multistage loading equal to

Results of fatigue tests of specimens of the tee welded joints

Type of loading	Sequence of application of load	N_{50}, thousand cycles	N_{50}^{str}, thousand cycles	N_{50}^{str}/N_{50}, %	Fracture
Multistage	Increasing	176.2	641.5	364	Stage 1, block 2
		176.2	930.6	528	Stage 4, block 2
		176.2	1274.1	723	Stage 2, block 3
	Decreasing	599.9	1656.0	276	Stage 3, block 4
		599.9	2075.6	346	Stage 2, block 5
		599.9	2378.1	396	Stage 4, block 5
	Quasi-random	230.3	1202.4	522	Stage 3, block 3
		230.3	1847.6	802	Stage 4, block 4
		230.3	2079.1	903	Stage 2, block 5
Block	Increasing	230.2	1909.6	830	Stage 4, block 8
		230.2	2297.2	998	Stage 2, block 10
		230.2	2409.0	1046	Specimen did not fracture
	Decreasing	230.2	1552.6	674	Stage 3, block 7
		230.2	1761.8	765	Stage 2, block 8
		230.2	2409.0	1046	Specimen did not fracture
	Quasi-random	230.2	1401.5	609	Stage 4, block 6
		230.2	2171.9	943	Stage 1, block 10
		230.2	2409.0	1046	Specimen did not fracture

Note. N_{50} — fatigue life of specimen in the non-strengthened state corresponding to 50 % accumulated fatigue damage under preset loading [5, 6]; N_{50}^{str} — fatigue life of specimen strengthened after accumulation of 50 % damage in the as-welded state under preset loading.

50 %, and under block loading — equal to 25 % of that of the specimen strengthened in the as-welded state.

Criterion for the completion of tests under the multistage and block loading conditions was complete fracture of the specimens. If under multistage loading the welded specimen strengthened after accumulation of 50 % damage in the as-welded state did not fracture after the set four loading stages (in one loading block) increased with respect to the initial ones, this loading block was repeated. Therefore, after strengthening, instead of multistage loading, the welded specimens were tested actually to complete fracture under the block loading conditions. The length of a block (quantity of the stress alternation cycles in one block) remained unchanged and equal to $481.6 \cdot 10^3$ cycles (see Figure 2).

Results of fatigue tests of specimens of the tee welded joints on steel 09G2S strengthened by the HFMP technology after accumulation of 50 % damage under the effect of differing multistage and block loadings are given in the Table by indicating the quantity of the running cycles before and after strengthening.

The experimentally established values of fatigue life under multistage loading of the tee welded joints strengthened by the HFMP technology after accumulation of 50 % damage (see the Table) show that these joints have a residual fatigue life ranging from 276 to 903 % of that of the non-strengthened joints. The values of the residual fatigue life obtained in testing the specimens under multistage loading with the increasing sequence of application of load are 364–723 %, with the decreasing sequence — 276–396 %, and with the quasi-random sequence — 522–903 % of those of the non-strengthened joints under the similar sequences of application of load. As follows from the results obtained, strengthening of the tee welded joints on steel 09G2S by the HFMP technology after accumulation of 50 % damage under the multistage loading conditions allows increasing the levels of the initially applied maximal stresses in a block to the stress levels corresponding to the values of high-cycle fatigue limits of the strengthened joints, and provide a guaranteed extension of their residual fatigue life.

Under block loading, for all sequences of application of load after running for two loading blocks in the as-welded state (50 % damage) and subsequent strengthening the specimens were subjected to the increased stress levels with the respect to the initial ones (see Figure 3). The specimens were tested to their complete fracture or running for 10 loading blocks in the strengthened state (see the Table). It was experimentally proved that after strengthening by the HFMP technology the scatter of the residual fatigue life values was within 609–1046 % of that of the non-strengthened specimens. The residual fatigue life values obtained in testing the specimens under block loading with the increasing sequence of application of load were within 830–1046 %, with the decreasing sequence — within 674–1046 %, and with the quasi-random sequence — within 609–1046 % of those of the non-strengthened welded joints under similar sequences of application of loads.

Therefore, it was experimentally proved that under multistage and block loading (see the Table) strengthening of the tee welded joints after accumulation of 50 % damage by the HFMP technology allows not only substantially increasing the levels of the applied stresses, but also extending their residual fatigue life from 3 to 10 times. Under block loading, the scatter of experimental values of cyclic fatigue life of the welded joints was within a narrower range (1,401,400–2,409,000 cycles) than under multistage loading (641,500–2,378,100), and did not depend on the sequence of application of load in a block.

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EFFECT OF HEAT TREATMENT ON SENSITIVITY OF THE HAZ METAL ON TITANIUM-STABILISED AUSTENITIC STEEL TO LOCAL FRACTURE

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The mechanism of embrittlement of the HAZ metal of welded joints on steel 12Kh18N12T was revealed. This mechanism was found to be associated with development of the processes of direct and relative softening of grain boundaries in welding and at high-temperature low-frequency low-cycle loading. The efficiency of austenising to improve local fracture resistance of the welded joint HAZ metal was experimentally proved.

Keywords: *arc welding, welded joint, austenitic steel 12Kh18N12T, heat-affected zone, structural and chemical microheterogeneity, evaluation of weldability, optical and electron microscopy, heat treatment — austenising, low-frequency low-cycle loading, local fracture*

No common opinion exists now about the efficiency of austenising as a reliable technological method for prevention of local fracture. Studies [1–3] show that austenising does not always give positive results, while deviation from the set parameters of heat treatment may lead to decrease in load-carrying capacity of welded joints. Therefore, a priori application of the known recommendations without proper evaluation of their effect on structure and properties of the HAZ metal of a specific welded joint may cause deterioration of operational reliability.

The purpose of this study was to reveal the mechanism of embrittlement of the HAZ metal on austenitic steel 12Kh18N12T under the technological and service thermal-deformation effects, and propose the efficient technological method for improving local fracture resistance of the welded joints under low-frequency low-cycle loading. The study was performed on lengths of 12Kh18N12T steel steam pipes with a diameter of 230 mm and thickness of 30 mm cut out after being in operation for 70,000 h to perform overhaul of a run of the steam pipe of boiler 2 in the turbine section of Cherepetskaya power plant. As known from the operation experience, this material is sensitive to local fracture. Therefore, it is expedient to use it as a test one. This material complies with requirements of the regulatory documents in its chemical composition (wt.%: 0.13 C, 1.21 Mn, 0.55 Si, 18.7 Cr, 12.4 Ni, 0.51 Ti) and mechanical properties.

Welded joints were made by the technology accepted to perform erection work on steam pipelines [4]. An annular asymmetric single-bevel groove was made in the pipes. One half of the groove was welded up by using 4 mm diameter electrodes of the TsT-15 grade, and the other — by using electrodes of the TsT-26 grade. The welded joints on steel 12Kh18N12T were tested in the as-welded state and after austenising at T = 1373 K with holding for 1 h and cooling in air.

The as-welded joints featured high heterogeneity of mechanical properties, K_σ, between the weld metal ($\sigma_{0.2WM}$) and base metal ($\sigma_{0.2BM}$): $K_\sigma = \sigma_{0.2WM}/\sigma_{0.2BM}$. Dimensionless criterion K_σ characterises the degree of three-dimensionality of the stressed state. At temperature T = 873 K, all the as-