INFLUENCE OF PRELIMINARY CYCLIC LOADING ON EFFECTIVENESS OF WELDED JOINT STRENGTHENING BY HIGH-FREQUENCY PEENING

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The paper gives the results of studying the effectiveness of application of high-frequency mechanical peening to improve the residual fatigue life of tee welded joints on low-alloyed steels with accumulated fatigue damage. It is shown that the effectiveness of strengthening welded joints by this technology can vary in a broad range, depending on operation duration and level of applied stresses during operation.

Keywords: *welded joints, fatigue, fatigue damage, high-frequency mechanical peening, cyclic fatigue life, strengthening effectiveness*

Fatigue strength of welded joints is improved considerably by application of various postweld treatments, known as methods of surface plastic deformation of metal. Systematic studies conducted at the PWI of the NAS of Ukraine lead to the conclusion that high-frequency mechanical peening (HFMP) ensures the highest physico-mechanical characteristics of the strengthened metal layer and at the current stage of development of resources-saving technologies is the most efficient method of strengthening the welded structures operating under the conditions of alternating loading. Effectiveness of application of this method of welded joint treatment at the stage of structure fabrication is quite well studied, and investigation results are widely represented in literature. A number of studies are devoted to investigation of the effectiveness of strengthening welded joints in operating metal structures, i.e. after the joints have accumulated the specified damage fraction [1–5]. It is experimentally established that after HFMP of welded joints with accumulated fatigue damage (right up to the moment of formation of a surface fatigue crack) the levels of applied maximum cycle stresses in the loading block, which are much lower that the endurance limit of the strengthened welded joint, have no damaging effect. On the other hand, the data obtained in these works on improvement of cyclic fatigue life of welded joints after a certain operation period differ considerably, that is indicative of the need to perform further studies in this direction.

So, in work [1] on the influence of preliminary cyclic loading on the effectiveness of strengthening by HFMP, treatment was conducted after welded tubular connections have operated for 25–60 % of their fatigue life in as-welded condition. The authors propose to determine the fatigue life of the connections by linear summation of fatigue damage before and after strengthening:

$$\sum \frac{n_i}{N_i} + \sum \frac{n_j}{N_j} \geq a,$$

where n_i, N_i is the number of operation cycles and cycles-to-failure at stress σ_i of as-welded joint; n_j, N_j is the number of operation cycles and cycles-to-fracture at stress σ_j of welded joint strengthened by HFMP technology in as-welded condition; a is the limit accumulated fatigue damage.

Proceeding from experimental data the authors suggest using a unity as the limit value of the sum of relative fatigue lives, i.e. the effectiveness of the increase of fatigue life of welded joints with accumulated fatigue damage by HFMP decreases with increase of the number of operation cycles before strengthening, and the maximum increase of fatigue life is achieved at strengthening right after welding.

In [2] the effectiveness of application of HFMP technology to tee welded joints of steel St3 after they have operated for 50 % of their fatigue life in as-welded condition at the load of $(0.7–0.9)\sigma_y$ was studied. Obtained fatigue curves demonstrate an increase of fatigue life of such samples by more than 2 times compared to samples strengthened by HFMP in as-welded condition. Such an increase of fatigue life in samples, pre-tested in as-welded condition before operation up to 50 % of their fatigue life, is attributed by the authors to the fact that high levels of applied stresses lead to formation of plastic strains in the stress raiser zones, and, therefore, to inducing residual compressive stresses in them. Subsequent HFMP treatment further raises the residual compressive stresses in the raiser zones. If the above formula is used for the results obtained in this work, then the limit total damage would be in the range $a = 2.5–3.1$.

In [5] treatment of welded tubular connections from steel 20 by HFMP was conducted both in as-welded condition, and after preliminary static loading at high stress levels. From the above fatigue curves it follows that strengthening after preliminary static loading is more effective (fatigue life increases by approximately 4 times), compared to strengthening of welded joints in as-welded condition. Such an increase is attributed both by the authors of this work, and the authors of [2], to higher levels of induced residual compressive stresses in the treatment zone.

Proceeding from the results of [1, 2], prediction of the effectiveness of strengthening by HFMP technology of welded joints after certain operation period, based on linear summation of fatigue damage, apparently should take into account the levels of applied alternating stresses before and after treatment.

The purpose of this work is to establish the influence of preliminary cyclic loading on the effectiveness of strengthening tee welded joints by HFMP.

Experimental investigations were conducted on samples of tee joints of low-alloyed steels 09G2S ($\sigma_y = 370$ MPa, $\sigma_t = 540$ MPa) and 10KhSND ($\sigma_y = 450$ MPa, $\sigma_t = 570$ MPa). Blanks for samples from these steels were cut out of rolled sheets so that the long side was oriented along the rolling direction. Transverse stiffeners were fillet welded from both sides by manual electric arc welding by UONI-13/55 electrodes (Figure 1). Thickness of experimental sample is due to wide application of 12 mm thick rolled stock in welded structures, and the width of its working part was selected, proceeding from testing equipment capacity. At joint strengthening by HFMP technology surface plastic deformation was applied to a narrow zone of weld metal transition to the base metal. Fatigue testing of samples was conducted in URS 20 machine at uniaxial alternating tension with cycle asymmetry $R_\sigma = 0$. All the samples were tested to complete fracture or their withstanding $2\cdot10^6$ stress alternation cycles. Calculation of damage fractions of welded joints of 09G2S and 10KhSND steels in the as-welded and as-strengthened condition was performed by fatigue curves obtained earlier and given in [6, 7].

Twelve welded samples from steel 09G2S were tested in unstrengthened condition at maximum stress cycles of 180 and 260 MPa up to 50 % of fatigue life at complete fracture. After that all the samples were strengthened by HFMP technology and fatigue testing was continued at higher levels of maximum cycle stresses.

Maximum stresses initially applied to welded samples, equal to 180 MPa, were increased up to levels of 260, 278 and 296 MPa (two samples on each stress level). In six samples tested in as-welded condition at specified initial maximum cycle stresses of 260 MPa, after HFMP treatment the applied stresses were increased up to levels of 275, 290 and 305 MPa (two samples on each stress level). Selection of maximum levels of cycle stresses before and after strengthening was performed so as to cover the entire range of applied loads, characteristic for the region of high-cycle fatigue of strengthened and unstrengthened tee welded joints.

Six samples from 10KhSND steel in unstrengthened condition were tested at regular loading with maximum cycle stresses of 280, 290 and 300 MPa (two samples on each stress level) up to accumulation of 50 % damage. After strengthening by HFMP of welded samples from 10KhSND steel applied loads remained the same, when fatigue tests were continued.

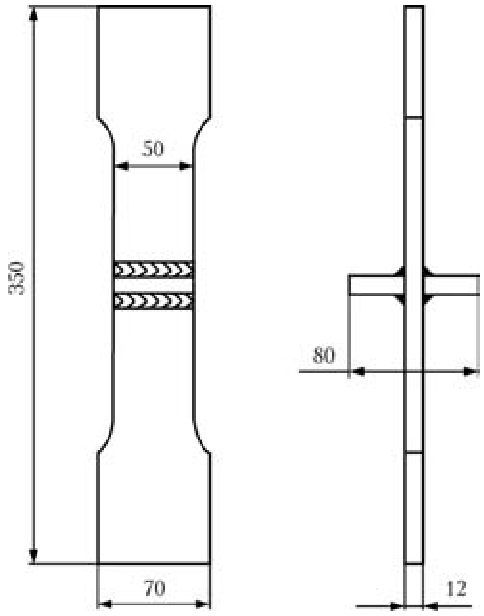

Figure 1. Schematic of an experimental sample of a tee joint of 09G2S steel

Results of fatigue testing of welded samples of 09G2S and 10KhSND steels are given in the Table.

Limit values of the sum of relative fatigue lives obtained on six samples of tee welded joints from 09G2S steel, strengthened by HFMP after testing up to 50 % of fatigue life at maximum stresses of 180 MPa, are in the range of 0.77–1.21. Here one sample did not fail after $2\cdot10^6$ cycles of stress alternation in as-strengthened condition (its total damage level was equal to more than 1.80). Limit values of total damage obtained on six samples from steel 09G2S, strengthened by HFMP after testing to 50 % of fatigue life at maximum stresses of 260 MPa, are in the range of 1.51–2.13. Testing of one of the six samples was interrupted after $2\cdot10^6$ cycles of stress alternation in as-strengthened condition (total damage level was more than 2.37). Total damage level of tee welded joints of 10KhSND steel, tested at unchanged regular loading before and after strengthening, is in the range of 2.37–2.87. Three samples from steel 10KhSND did not fail after testing for $2\cdot10^6$ cycles of stress alternation in as-strengthened condition.

Obtained results are indicative of the fact that under the conditions of regular loading the limit values of the sum of relative fatigue lives of tee welded joints on low-alloyed steels, strengthened by HFMP at accumulation of 50 % of damage in unstrengthened condition, depend on the levels of alternating stresses applied to welded joints before their strengthening. This is related to the fact that the high levels of stresses applied to welded joints before strengthening can lead

Results of fatigue testing of samples of tee welded joints of 09G2S and 10KhSND steels strengthened by HFMP after testing to 50 % fatigue life in as-welded condition

Sample number	As-welded condition			Strengthened condition			$\sum \frac{n_i}{N_i}$, %
	$\sigma_{1\max}$, MPa	n_1, thou cycles	n_1/N_1, %	$\sigma_{2\max}$, MPa	n_2, thou cycles	n_2/N_2, %	
09G2S steel							
1	180	500	50	260	798.8	51.6	101.6
2	180	500		260	>2000*	>130	>180
3	180	500		278	707.0	70.7	120.7
4	180	500		278	357.5	35.8	85.8
5	180	500		296	174.7	27.2	77.2
6	180	500		296	185.3	28.9	78.9
7	260	64		275	>2000*	>186.5	>236.5
8	260	64		275	1315.6	122.7	172.7
9	260	64		290	751.1	101.1	151.1
10	260	64		290	1011	136.1	186.1
11	260	64		305	839.5	163.2	213.2
12	260	64		305	580.8	112.9	162.9
10KhSND steel							
1	280	79.7	50	280	>2000*	>172.8	>222.8
2	280	79.7		280	>2000*	>172.8	>222.8
3	290	67.8		290	1820.3	215.5	265.5
4	290	67.8		290	>2000*	>236.9	286.9
5	300	57.7		300	1153.5**	187.3	237.3
6	300	57.7		300	1314.8	213.4	263.4

* — no failure; ** — failure in the base metal.

to partial or complete relaxation of residual tensile welding stresses across the entire sample section, and in some cases — can induce residual compressive stresses in the stress raiser zones. For an approximate determination of maximum cycle stresses $\sigma_{\max}$, at which complete relaxation of residual stresses is achieved, we can proceeded from $\sigma_{\max} > > \sigma_y/\alpha_\sigma$ inequality, where α_σ is the stress concentration factor. As is seen from the Table, such a relaxation of residual welding stresses before performance of HFMP of welded joints with accumulated 50 % damage, increases their residual fatigue life by approximately 1.1–2.4 times, compared to fatigue life of joints strengthened in as-welded condition.

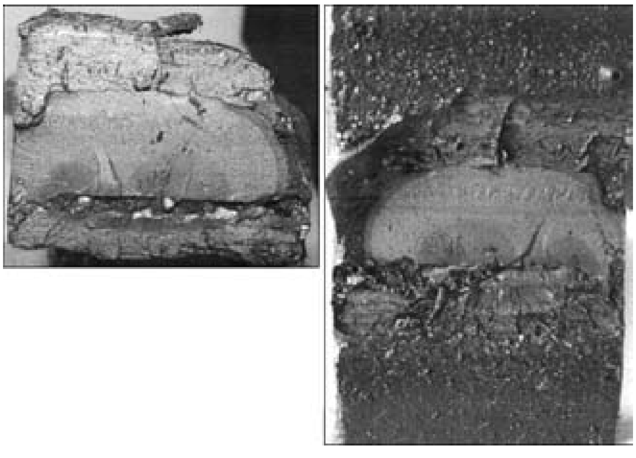

Figure 2. Fatigue fracture of a sample of 09G2S tee joint strengthened by HFMP after testing to 10 % damage level

Generalizing the results of fatigue testing and results of [1, 5, 6], one may assume that the duration of testing at high levels of applied external loading before strengthening also has a significant influence on effectiveness of strengthening by HFMP. Six samples of a tee welded joint from 09G2S steel were additionally tested by the following procedure. Welded joints were tested in unstrengthened condition at maximum cycle stresses of 260 MPa up to achieving 10, 30 and 70 % fatigue life at complete fracture, two samples for each testing level, and then strengthened by HFMP technology. After sample strengthening, fatigue testing was continued at the level of maximum cycle stresses of 305 MPa.

Failure of the first sample pre-tested to 10 % fatigue life, occurred after 1,871,300 cycles of stress alternation in the base metal, i.e. welded joint fatigue life increased by more than 3.5 times, compared to as-welded condition. The second sample failed (Figure 2) in the zone of weld metal transition to non-load bearing stiffener after 1,614,600 cycles of stress alternation. As is seen from Figure 2, fatigue crack initiation and subsequent failure of the welded sample occurred because of incomplete penetration of one of the stiffeners joined by fillet welds.

After pre-testing of the third and fourth samples to 30 % fatigue life before strengthening at specified maximum cycle stresses of 260 MPa, they failed at 1,168,500 and 1,407,200 cycles of stress alternation, i.e. the joint fatigue life increased by 2–3 times compared to strengthening in as-welded condition.

Pre-testing to 70 % fatigue life at specified maximum cycle stresses did not lead to a noticeable increase of fatigue life. Failure of the fifth and sixth sample occurred after testing by 452,900 and 628,400 cycles of stress alternation in as-strengthened condition, respectively, i.e. residual fatigue life of joints with such test cycle numbers after strengthening by HFMP remains on the level of fatigue life of joints strengthened in as-welded condition.

Obtained experimental data are indicative of the fact that under the conditions of regular loading the effectiveness of strengthening by HFMP of welded joints with accumulated fatigue damage increases with increase of the level of applied alternating stresses before strengthening and with shortening of the duration of testing in as-welded condition. The latter can have the following explanation. High levels of applied stresses lead to relaxation of residual welding stresses in the stress raiser zones already after the first loading cycles without any significant accumulation of fatigue damage. Subsequent loading cycles (increase of testing duration) lead only to an intensive accumulation of fatigue damage. Thus, in order to increase the HFMP effectiveness, it is rational to try and reduce the duration of the impact of high stress levels before strengthening. Therefore, the maximum characteristics of fatigue strength of welded joints can be achieved at HFMP strengthening after preliminary static overloading. This is confirmed by the data of [5], where it is established that after preliminary static loading causing stresses close to the yield point in the raiser zones, the fatigue life of HFMP strengthened welded tubular connections from steel 20 rises 4 times, compared to strengthening in as-welded condition.

Thus, depending on the duration of testing and level of relaxation of residual welding stresses in the stress raiser zone in service, the effectiveness of welded joint strengthening by HFMP can vary in a broad range (limit values of the sum of relative fatigue lives $a = 0.77$–4). For approximate evaluation of the effectiveness of HFMP strengthening of welded joints which were not exposed to high loading levels in service before strengthening, a unity can be taken as the limit value of the sum of relative fatigue lives.

CONCLUSIONS

1. It is established that under the conditions of regular loading, the effectiveness of HFMP strengthening of welded joints with accumulated fatigue damage depends on the level and duration of the impact of applied loading.

2. It is shown that residual fatigue life of highly loaded tee welded joints of low-alloyed steels after HFMP strengthening at 70 % accumulated damage is not inferior to fatigue life of joints strengthened in as-welded condition. Shortening duration of testing of such joints from 70 to 10 % of their fatigue life increases the strengthening effectiveness up to 3.5 times compared to strengthening in as-welded condition.

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