INCREASE OF CYCLIC FATIGUE LIFE OF TEE WELDED JOINTS WITH SURFACE CRACKS

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Investigation results on the efficiency of using high-frequency mechanical peening to increase the fatigue resistance of tee welded joints on low-alloy steels containing fatigue cracks on their surface are presented. Two approaches to strengthening tee joints damaged by fatigue cracks are considered.

Keywords: *welded structures, structural steels, tee welded joints, cyclic fatigue life, high-frequency mechanical peening, fatigue crack, strengthening technology*

At the stage of designing welded products or structures operating under the conditions of alternating loading, absence of fatigue damage in them is envisaged for the entire design service life. However, practical experience has shown that in welded structures for various applications, meeting the code requirements to their design and fabrication, fatigue cracks start appearing already at an early stage of operation of constructions or machines [1]. Being the most dangerous kind of defects, fatigue cracks essentially lower the cyclic fatigue life of the damaged elements and structure as a whole.

Replacement of damaged structures by new ones requires considerable expenditure and time, so that the damaged elements of large-sized structures are more and more often subjected to various repair-restoration operations, instead of replacing them. The following can be regarded as the most widely spread types of such repair operations: hole drilling in the crack tips with subsequent mounting of high-strength bolts with their tightening, repair welding with subsequent strengthening, redistribution of post-weld stresses and working loads, inducing favourable residual compressive stresses near the crack tips, etc. [2, 3]. These types of operations are mainly applied in large-sized welded structures, in which the presence of through-thickness fatigue cracks of 20 mm and greater length does not lead to any essential lowering of the load-carrying capacity.

On the other hand, we cannot limit ourselves to just the repair-restoration operations on the damaged parts, as cracks may develop with a high degree of probability in similar components and elements. Therefore, in repair of welded products and constructions their most loaded sound welded joints and joints with shallow surface fatigue cracks should be subjected to strengthening.

It is known that high-frequency mechanical peening (HFMP) of sound welded joints with 50 % and higher level of accumulated fatigue damage significantly improves their fatigue resistance characteristics [4].

Strengthening by other technologies of surface plastic deformation (SPD) of welded joints, containing surface semi-elliptical cracks of a small depth, improves the cyclic fatigue life up to 10 times, depending on the kind of strengthening treatment and crack depth. So, in [5] it is noted that shot blasting of Waspalloy samples with fatigue cracks of 0.67 mm and shorter length increases the sample fatigue resistance 3 times, and at treatment of more than 1 mm cracks no improvement of fatigue resistance is found. In [6] it is shown that peening of tee welded joints with fatigue cracks by a puncher promotes increase of cyclic fatigue life 1--10 times, depending on the crack size. At peening by a puncher of a crack of 1.0–1.5 mm depth, the cyclic fatigue life increases 10 times, at peening of a crack of about 3 mm depth — by 1--2.5 times, and at peening of a crack more than 5 mm deep no fatigue life improvement is found. Such a difference in the results is due to different depth of the zone of inducing residual compressive stresses of 0.33 and 2.5 mm at shot blasting and puncher treatment, respectively.

Improvement of fatigue life is observed also at application of strengthening treatments to samples with through-thickness fatigue cracks, and their effectiveness essentially depends on metal thickness [7, 8]. In [7] the results of studying the cyclic crack resistance produced on compact samples 12.5 mm thick with the initial 3 mm crack, point to a slight improvement of the sample fatigue life: after shot blasting — by 1.2 times, and after peening by single-pin puncher — by 2 times. At small metal thicknesses SPD technologies cause a more significant increase of cyclic fatigue life. In [8] after shot blasting of compact samples 4.2 mm thick with initial 4 mm crack an increase of their fatigue life 2--4 times is noted, depending on the location of the peening zone relative to the crack tip.

The above-mentioned publications demonstrate an increased interest to repair-restoration operations on welded joints with surface fatigue cracks by their strengthening by SPD technologies.

There are no published experimental data on improvement of cyclic fatigue life of welded joints with surface fatigue cracks by application of HFMP technology. On the other hand, in [9] it is noted that

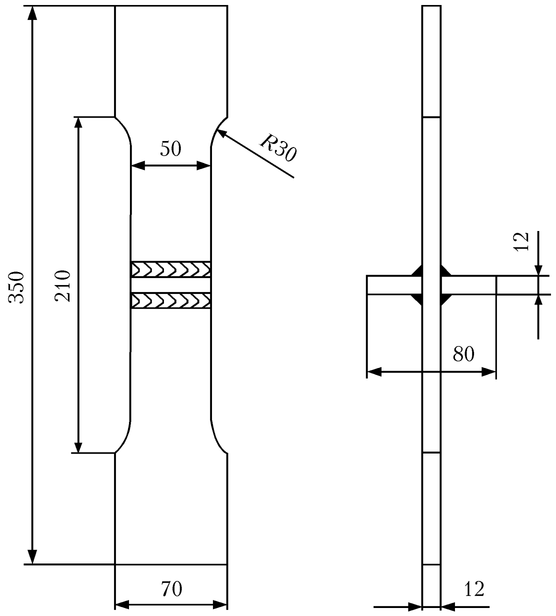

Figure 1. Schematic of a sample of tee welded joint with two transverse stiffeners

strengthening by HFMP technology results in inducing residual compressive stresses on the base metal surface down to 1.7 mm depth. For the case of welded joints (as a result of interaction with the residual tensile stresses) the layer of HFMP induced compressive stresses decreases to the depth of about 1 mm. On the other hand, a 2–3 times increase of the threshold stress intensity factor is noted at HFMP treatment of welded joints in as-welded condition. This leads us to believe that HFMP will turn out to be an effective technology for improvement of fatigue resistance of welded joints with shallow surface cracks.

The purpose of this work is determination of the effectiveness of HFMP technology application to improve the fatigue resistance of tee welded joints on low-alloyed steels with surface fatigue cracks and establishing the features of strengthening of such joints.

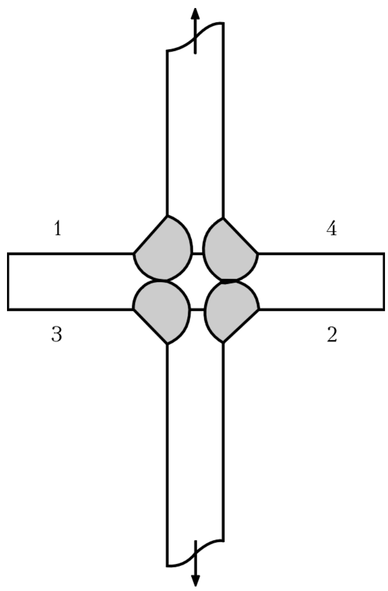

Figure 2. Schematic of a fragment of the tee welded joint with numbered near-weld zones

Experimental studies were conducted on samples of tee joints of steel 09G2S (σ_y = 370 MPa, σ_t = = 540 MPa) and 10KhSND (σ_y = 457 MPa, σ_t = = 565 MPa). Blanks for the samples were cut out of rolled sheets so that their long side was oriented along the rolling direction. Transverse stiffeners were welded by fillet welds from both sides by full-penetration manual arc welding by UONI-13/55 electrodes. The shape and geometrical dimensions of the sample were selected (Figure 1) proceeding from the testing equipment capacity. At joint strengthening by HFMP technology surface plastic deformation was applied to a narrow zone of weld metal transition to base metal. Fatigue testing of samples was conducted in URS 20 testing machine at zero-to-tension alternating cycle.

First the effectiveness of HFMP technology application to improve the cyclic fatigue life of the joints was established, depending on the crack depth. Welded sample of 10KhSND steel was tested at maximum cycle stresses σ_{max} = 280 MPa, and three samples of steel 09G2S were tested at σ_{max} = 180 MPa. After formation of a fatigue crack of the specified length in one of the zones of the weld-to-base metal transition in the tee joint sample, testing was interrupted and strengthening of all the four zones by HFMP technology was performed (Figure 2). After strengthening, testing was carried on up to complete failure of the sample or its withstanding $2\cdot10^6$ stress reversal cycles in the as-strengthened condition.

Determination of the parameters of non-through-thickness surface cracks was performed using fractographic and dye penetrant control techniques. Combination of both the methods allowed determination of parameters of non-through-thickness fatigue crack in the joint by sample fracture before its strengthening. A mixture of kerosene with synthetic oil was used as the penetrant. After strengthening by HFMP technology addition of penetrant into the cavity was stopped.

In the first sample a 5 mm fatigue crack developed after the sample has withstood 232,800 stress reversal cycles. After strengthening of all the four near-weld zones no new cracks initiated until the sample has withstood $2\cdot10^6$ stress reversal cycles in the as-strengthened condition.

In the second sample the fatigue crack 10 mm long initiated in one of the near-weld zones after 344,100 stress reversal cycles. After strengthening by HFMP no fatigue cracks initiated in other zones of the welded joint.

In the third sample about 23 mm long crack formed near one of the fillet welds after 428,600 stress reversal cycles. After strengthening by HFMP the sample failed along the damaged weld after 418,200 stress reversal cycles in as-strengthened condition.

In the welded joint of 10KhSND steel (fourth sample) a fatigue crack 7 mm long formed in the zone of

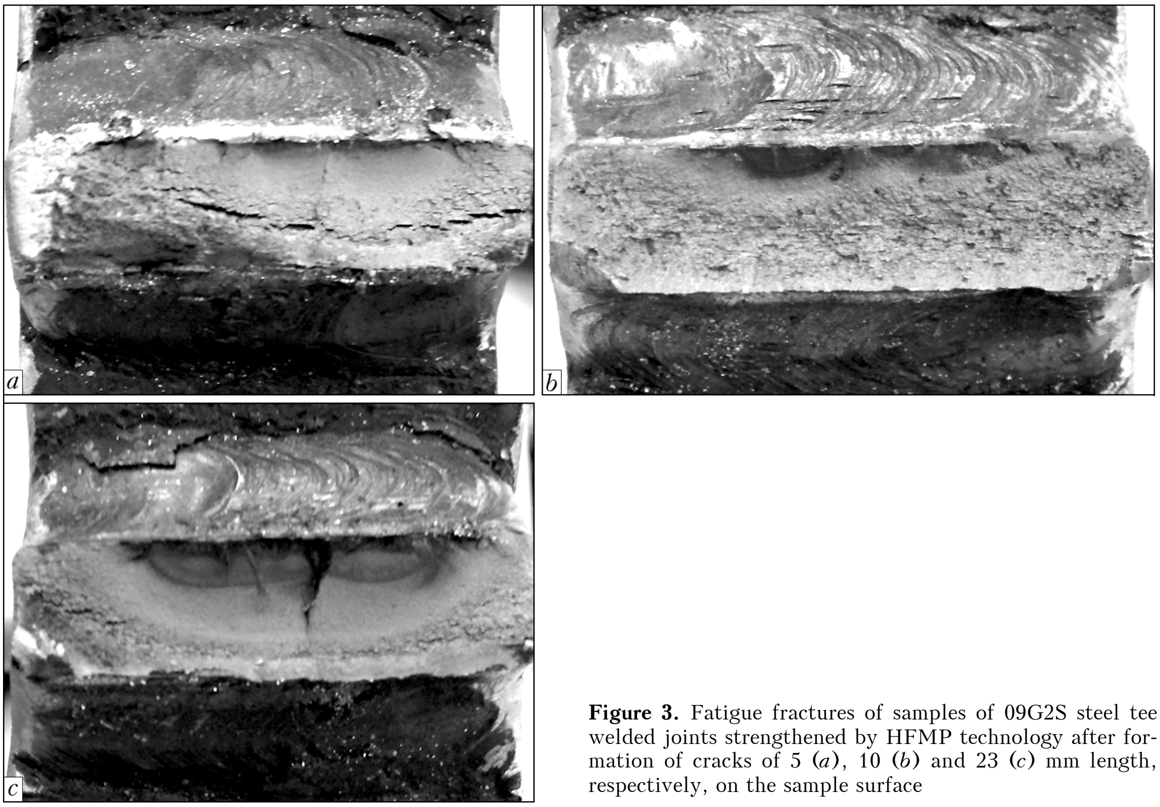

Figure 3. Fatigue fractures of samples of 09G2S steel tee welded joints strengthened by HFMP technology after formation of cracks of 5 (*a*), 10 (*b*) and 23 (*c*) mm length, respectively, on the sample surface

weld transition to the base metal after 178,400 stress reversal cycles. After strengthening by HFMP no fatigue crack formation in other zones was observed up to $2 \cdot 10^6$ stress reversal cycles.

To measure crack depth in those samples, which did not fail up to $2 \cdot 10^6$ stress reversal cycles in as-strengthened condition, sample complete breaking up was achieved by increasing the maximum cycle stresses up to 320 MPa. Figure 3 shows fractures of samples of 09G2S steel tee joints strengthened by HFMP technology after formation of cracks of different length on the sample surface. Fractographic analysis of fractures showed that the ratio of fatigue crack length on sample surface and its depth is equal to 5:1. Proceeding from the obtained results in further studies we will apply plastic deformation to surface fatigue cracks of approximately 1 mm depth (5 mm length of the crack on the surface).

To study the effectiveness of HFMP application to improve the fatigue resistance of welded structures, the elements of which have fatigue cracks of about 1 mm depth, fatigue testing of two tee welded joints from low-alloyed steel was conducted by the following procedure. One sample of 10KhSND steel in the initial condition was tested at uniaxial alternating tension with the constant maximum cycle stress, the second sample of 09G2S steel was tested at block loading (Figure 4). Samples were tested up to development of approximately 1 mm deep crack in one of the four zones of transition of the fillet weld metal to the base metal (see Figure 2). After that the zone damaged by the crack was strengthened by HFMP technology. Fatigue testing of the strengthened sample was continued up to appearance of the next crack approximately 1 mm deep in one of the fillet weld zones unstrengthened by HFMP. The zone damaged by fatigue crack was also strengthened by HFMP technology and sample fatigue testing was carried on. After similar testing of the third and fourth zones damaged by the fatigue crack, the strengthened sample was further tested at unchanged stress level up to fracture or up to $2 \cdot 10^6$ cycles.

Tested for fatigue by the above procedure the first welded sample of 10KhSND steel at maximum cycle stresses σ_{max} = 220 MPa demonstrated the following. The first fatigue crack developed in the zone of fillet weld-to-base metal transition (see Figure 2, zone 1) after 267,300 stress reversal cycles. As follows from the *S*--*N* curve of these samples given in [10], fatigue life of the sample up to formation of the first crack of approximately 1 mm depth is equal to 69 % of fatigue life of the sample to complete fracture. The second fatigue crack formed in the transition zone near the opposite stiffener (zone 2) after 587,200 stress reversal cycles, which is equal to 145 % of sample

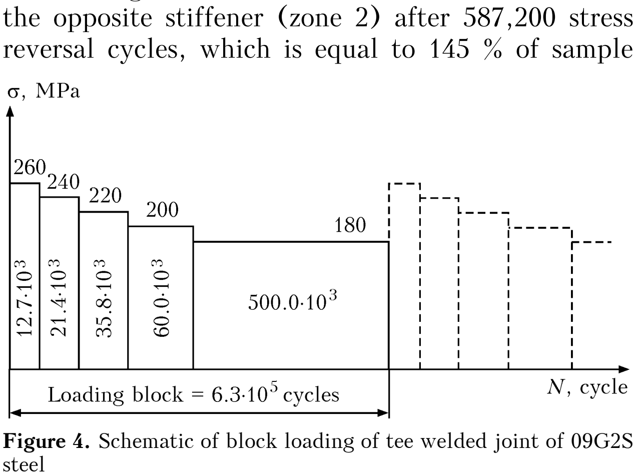

Figure 4. Schematic of block loading of tee welded joint of 09G2S steel

fatigue life up to compete fracture. The third crack developed after 1,318,300 stress reversal cycles (zone 3), which is equal to 330 % of fatigue life of the sample up to complete fracture. After HFMP treatment of three zones of fillet weld-to-base metal transition, where fatigue cracks formed successively, formation of the fourth crack in the fillet weld zone unstrengthened by HFMP (see Figure 2, zone 4) was not observed up to total fatigue life of the sample of 2,226,100 stress reversal cycles. After that fatigue testing of the sample was interrupted.

The second sample was tested at five-step block loading at the initial stress level of 260 MPa with subsequent decrease to 180 MPa with 20 MPa step. Number of cycles in each loading step is shown in the schematic given in Figure 4. After successive strengthening by HFMP of all the zones damaged by fatigue cracks testing was carried on under the specified block loading up to fracture. Testing results are given in the Table. Considering that before appearance of the third crack the total fatigue life of the sample was equal to approximately $2.6 \cdot 10^6$ stress reversal cycles (350 % of fatigue life of the sample in the initial condition to complete fracture), no strengthening of the third and fourth zone by HFMP technology was performed. Sample failure occurred in the unstrengethened zone after 2,723,200 stress reversal cycles in the second step of the fifth loading block (Table). The established values of cyclic fatigue life of the tee joint corresponding to formation of fatigue cracks of the specified length (depth) in four near-weld zones of fillet welds, point to a significant difference of fatigue resistance characteristics of these zones.

As is seen from the above results of tee sample testing, successive strengthening of the zones of fillet weld-to-base metal transition damaged by fatigue cracks of approximately 1 mm depth essentially improves the cyclic fatigue life of the joints. However, during performance of repair operations it is not rational to limit ourselves to strengthening of just the tee welded joint zone damaged by the fatigue crack, as furtheron cracks will initiate in the unstrengthened near-weld zones of the joint during their further operation. More effective is strengthening of all the four near-weld zones of the welded joint after formation in one of them of a fatigue crack of about 1 mm depth. This is confirmed by the results of fatigue testing given at the beginning of the article for samples of tee welded joints of 09G2S steel, which are shown in Figure 5 in the form of dark and light dots.

Figure 5 also gives the *S–N* curve of tee welded joints on 09G2S steel in the initial condition with 95 % confidence interval. Considering that the *S–N* curve is plotted from complete fracture of the samples, HFMP strengthening of the zone of transition of the weld metal-to-base metal with 4.5 mm deep fatigue crack does not lead to increase of cyclic fatigue life of the tee welded joint, as the fatigue life of the strengthened sample up to its fracture falls within the

Results of fatigue testing of a sample of 09G2S steel tee welded joint at block loading

Sample #	1st loading			2nd loading			3rd loading		
	$\sigma_{1\,max}$, MPa	n_1, thou cycles	n_1/N_1, %	$\sigma_{2\,max}$, MPa	n_2, thou cycles	n_2/N_2, %	$\sigma_{3\,max}$, MPa	n_3, thou cycles	n_3/N_3, %
1	260	12.7	10	240	21.4	10	220	35.8	10
2	260	12.7	10	240	21.4	10	220	35.8[2]	10
3	260	12.7	10	240	21.4	10	220	35.8	10
4	260	12.7	10	240	21.4	10	220	35.8	10
5	260	12.7	10	240	15.6[5]	7.3	–	–	–

Table (cont.)

Sample #	4th loading			5th loading			Testing features
	$\sigma_{4\,max}$, MPa	n_4, thou cycles	n_4/N_4, %	$\sigma_{5\,max}$, MPa	n_5, thou cycles	n_5/N_5, %	
1	200	60	10	180	500[1]	50	[1]HFMP of zone 1 (Figure 2) after 118,000 cycles
2	200	60	10	180	500	50	[2]HFMP of zone 2 (Figure 2) after 13,100 cycles
3	200	60	10	180	500	50	–
4	200	60	10	180	500[4]	50	[4]Crack 1 mm deep in zone 3 after 400,000 cycles
5	–	–	–	–	–	–	[5]Sample failure

Note. n_i --- number of cycles withstood by unstrengthened sample at *i*-th stress level; N_i --- number of cycles up to fracture of unstrengthened sample at *i*-th stress level.

95 % confidence interval of *S*–*N* curve for unstrengthened samples in the initial condition (Figure 5, points *3* and *3′*). Treatment of the near-weld zone at earlier stages of fatigue crack development (crack depth of 1 and 2 mm) essentially increases the cyclic fatigue life of the welded joint (points *1* and *1′*, *2* and *2′* in Figure 5). As shown above, after samples with fatigue cracks of 1 and 2 mm depth withstood $2\cdot10^6$ stress reversal cycles in as-strengthened condition, no propagation of the existing cracks or initiation of new cracks was observed. These samples failed at higher maximum cycle stresses equal to 320 MPa after another 35,100 and 37,200 stress reversal cycles, respectively, which was equal to about 130 % of the fatigue life of a welded sample in the initial condition corresponding to this loading level (see *S*–*N* curve in Figure 5).

Thus, strengthening of all the four near-weld zones of the welded joint after formation of a fatigue crack of approximately 1 mm depth in one of them allows not only restoring the fatigue life of the damaged sample to the initial level, but also significantly increasing its cyclic fatigue life.

CONCLUSIONS

1. An essential difference of fatigue resistance of four near-weld zones of fillet welds in tee joints of low-alloyed steels is established. The difference between the cyclic fatigue life of near-weld zones of fillet welds in these joints before formation of a fatigue crack approximately 1 mm deep can be more than 9 times.

2. Successive strengthening by HFMP technology of the near-weld zones with the formed fatigue cracks approximately 1 mm deep more than 3.5 times improves the cyclic fatigue life of the tee welded joint at constant or block loading compared to the initial condition.

3. In repair in order to achieve a maximum improvement of the cyclic fatigue life of tee welded joints it is rational to strengthen by HFMP technology all the four near-weld zones of such joints after formation of a fatigue crack approximately 1 mm deep in one of them. Three samples strengthened by such a procedure with the formed fatigue cracks after 178,400; 232,800 and 344,100 stress reversal cycles did not fail after $2\cdot10^6$ cycles in the as-strengthened condition.

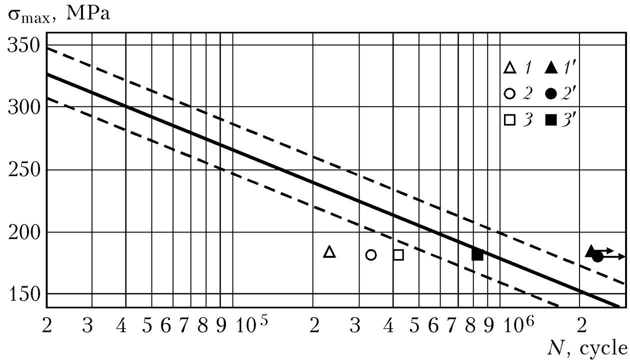

Figure 5. *S*–*N* curve of 09G2S steel tee joints in the initial condition with 95 % confidence interval and results of fatigue testing of three samples: *1*–*3* — up to formation of a crack 1, 2 and 4.5 mm deep, respectively; *1′*–*3′* — after HFMP strengthening

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