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APPLICATION OF HIGH-FREQUENCY PEENING TO IMPROVE THE PERFORMANCE OF BUTT WELDED JOINTS IN THE ATMOSPHERE OF TEMPERATE CLIMATE

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The paper presents the results of investigations of the effectiveness of application of high-frequency mechanical peening (HFMP) to improve fatigue resistance characteristics of butt welded joints in metal structures operating in an atmosphere of temperate climate. Metallographic studies showed that HFMP treatment of fusion zone in butt welded joint of 15KhSND steel before exposure to high humidity conditions promoted an improvement of corrosion resistance of this zone: reduction of corrosion pit depth and of extent of HAZ damage from 100 % practically to 0. Fatigue testing of welded joints in the initial and HFMP strengthened states was performed before and after exposure to high humidity and temperature. It is found that HFMP strengthening of butt welded joints of 15KhSND steel before exposure allows increasing fatigue strength at $2\cdot10^6$ cycles by 39 % and cyclic fatigue life up to 9 times. 16 Ref., 2 Tables, 5 Figures.

Keywords: *butt welded joint, fatigue, high-frequency mechanical peening, high humidity*

Welded metal structures in long-term service (bridges, bridge crossings, main pipelines, etc.) are expensive constructions, of which high safety requirements are made. As shown by statistics, 70–80 % of failures of welded metal structures are associated with damage of welded joints, despite the fact that their volume is equal to just about 1.0–1.5 % of total volume of the structure [1]. Fatigue is one of the most common types of fractures of welded metal structures, including bridge structures. Climatic factors of external environment essentially lower fatigue resistance of welded joints through involvement of the corrosive medium into the fracture process, resulting in corrosion damage (pitting, caverns, etc.), which are the geometrical stress raisers. Various methods are used for protection from corrosion-fatigue damage, including surface plastic deformation (SPD) of metal [1–4].

High-frequency mechanical peening (HFMP), known in foreign publications as ultrasonic impact treatment [5–8], takes up an important place among SPD methods. High effectiveness of application of this technology to improve the corrosion and fatigue resistance of welded joints was established at direct testing in corrosive solutions [9–12]. During such testing performance, the time of contact of samples with corrosive medium is from 10 up to 200 h. In recent years there have been publications devoted to investigation of long-term influence of corrosive media on the state of metal layer, plastically deformed by HFMP technology, and, accordingly, on the change of the level of induced residual compressive stresses and fatigue resistance characteristics [13–15].

Considering the location of climatic region of Ukraine, it is of interest to evaluate the long-term influence of temperate climate atmosphere on lowering of cyclic life of welded joints in the initial and HFMP strengthened states. As requirements of corrosion resistance (metal loss rate, corrosion defect size, etc.) at the impact of high humidity and temperature are made of metal structures, operating in temperate climatic conditions, the characteristic damage can be obtained by conducting accelerated corrosion testing in G4 moisture chamber.

The objective of this work is evaluation of the effectiveness of HFMP technology application to improve the fatigue resistance characteristics of butt welded joints at the stage of fabrication of metal structures, long-term operation of which will proceed in the atmosphere of temperate climate.

Material and investigation procedure. Investigations were conducted on samples of butt welded joints of structural low-alloyed steel 15KhSND, which is widely applied for fabrication of elements of metal structures for long-term operation (for instance, in span structures of railway and car bridges), has higher strength, and good weldability, is stable in atmospheric conditions and operable in the temperature range from –70 °C up to 45 °C. Chemical composition of the studied steel, wt.% was as follows: 0.142 C; 0.466 Si; 0.63 Mn; 0.020 S; 0.013 P; 0.31 Ni; 0.66 Cr; 0.34 Cu.

Blanks for samples of butt welded joints of 600×175 mm size were cut out of hot-rolled plates 12 mm thick of category 12 in the rolling direction. Butt welded joints were produced by automatic single-arc square butt welding of plates from two sides (0 to 1.0 mm gap in the butt), using OP 192 flux (Oerlikon Company) and Sv-08G1NMA wire of 4 mm diameter. Reverse polarity welding was performed with power supply from electric rectifier VSZh-1600. Modes of making the first weld were as follows: $U = 55$ V; $I = 650–700$ A; $v = 26.7$ m/h; for second weld (on the opposite side): $U = 57$ V; $I = 760–780$ A, $v = 26.7$ m/h. The second weld was made after complete cooling of the first one. Eight samples of 350×70 mm size were cut out of each 600×350 mm welded plate (Figure 1).

Fatigue testing was conducted in servohydraulic machine URS-20 at alternating tension with cycle asymmetry $R_\sigma = 0$ and 5 Hz frequency. The criterion of testing completion was total fracture of the samples or exceeding the test base of $2\cdot10^6$ stress alternation cycles.

Four series of samples of butt welded joints were tested:

- samples in as-welded (unstrengthened) state (first series);
- samples strengthened by HFMP technology (second series);
- samples in unstrengthened state after exposure to high humidity for 1200 h (third series);
- HFMP strengthened samples after exposure to high humidity for 1200 h (fourth series).

Strengthening of welded joints by HFMP technology was conducted with USTREAT-1.0 unit, in which manual compact impact tool with peizoceramic transducer is connected to ultrasonic generator with 500 W output power. A narrow zone of weld metal transition to the HAZ (fusion line) was subjected to surface plastic deformation. A single-row four-striker attachment with 3 mm striker diameter was used as strengthening device. The speed of HFMP performance at treatment of butt welded joints was 2 mm/s, amplitude of vibrations of manual impact tool end face was 25 μm.

Corrosion testing of samples of series 3 and 4 was conducted under the conditions, simulating temperate climate atmosphere (in moisture chamber at the temperature of 40 °C and air humidity of 98 %), for 1200 h that is equivalent to 12 years of operation (substantiation of testing duration and conditions are given in the procedure [16]).

After corrosion testing the method of optical microscopy was used to study the change of the condition of surface layer of near-weld zone of butt welded joints in unstrengthened and HFMP strengthened states. Metallographic sections were studied in Neophot-32 microscope, digital image of the structure was obtained with digital camera Olympus C5050. Microhardness was measured with microhardness meter M-400 of LECO Company at 50 g (0.49 N) load.

Investigation results. Metallographic investigations established the following. Grain size, HAZ extent and microstructure of the first and second welds are practically the same. Directly near the welded joint surface coarse-grained zone (CGZ) of about 0.8 mm length contains No.5 (less often, No.4 and No.6) grains; grain size in fine-grained zone (FGZ) of about 1.3 mm length is Nos 7–10 (Figure 2, *a*). At about 2 mm distance from the surface CGZ size increases to 2 mm, and grain size — up to Nos 3–4. CGZ metal structure in deeper-lying layers from rolled stock surface is ferritic with densely distributed precipitates of MAC-phase (with ordered platelike precipitates of upper bainite type with about 108 μm length of individual plates). Chaotically distributed quite large particles of grain type are found. Grain boundaries are outlined by relatively wide, up to 5–8 μm, interlayers of intergranular polygonal ferrite. In CGZ surface layers ferrite grains were also observed, which had densely distributed MAC-phase of the type of upper and lower bainite with polygonal ferrite precipitates in the form of wider interlayers or stringers of individual grains located along their boundaries. Microhardness of metal of HAZ surface layers of the first and second welds in the initial state is equal to *HV*0.49-168–223 (Table 1).

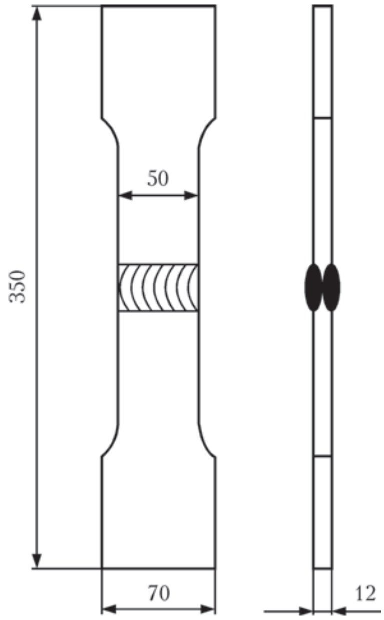

Figure 1. Shape and geometrical dimensions of samples of butt welded joint

After HFMP, grooves of practically the same size shifted towards the HAZ or into weld metal, formed in the zone of weld fusion with base metal in surface layers of weld and HAZ metal. Depth of plastically deformed metal layer under the groove was equal to about 260–325 μm (Figure 2, *c*). Intensive deformation (elongation) of grains was observed both in coarser ferrite grains with MAC-phase precipitates and in HAZ ferrite grains free from precipitates, and in cast bainite-ferrite grains of the weld. Deformed grains are located at an angle to metal surface around the groove perimeter, grain form coefficient is equal to $K_f = 8–20$ ($K_f = a/b$, where *a* and *b* are elongated grain length and width, respectively). Micro-

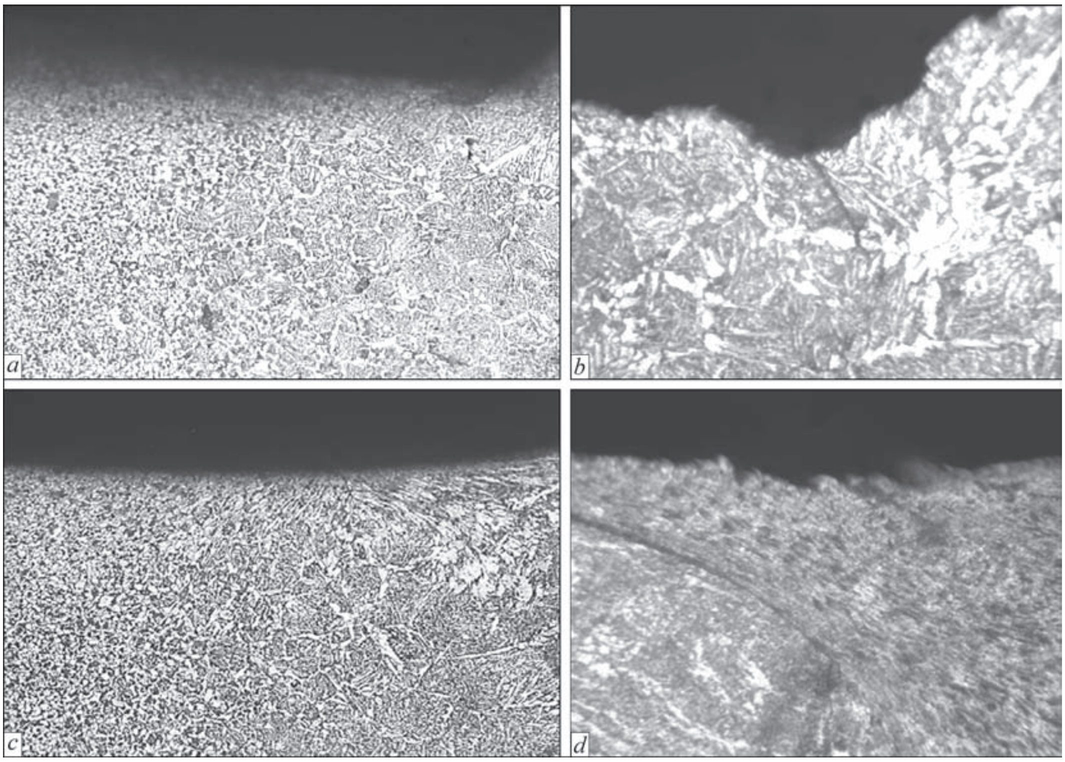

Figure 2. Microstructure of surface layer of HAZ metal, unstrengthened (*a*, *b*) and strengthened by HFMP technology (*c*, *d*), in butt welded joint in the initial state (*a*, *b*) and after corrosion testing at high humidity for 1200 h (*b*, *d*); *a*, *c* — x156; *b*, *d* — ×400

hardness of plastically deformed metal of HAZ surface layers is equal to *HV*0.49-177–232 (Table 1) that is by 8–10 % higher than microhardness of HAZ metal surface layer in the initial condition.

After exposure under the conditions of high humidity, a non-uniform layer of corrosion products formed on the surface of both strengthened and unstrengthened samples (Figure 3). As fatigue cracks usually form along the fusion line, corrosion damage in the zone of weld metal transition to base metal was studied. In keeping with GOST 9.908 corrosion is identified as continuous non-uniform. The main types of corrosion in surface layers of HAZ metal are corrosion spots and pits of different dimensions. In unstrengthened welded joints the depth of corrosion pits in surface layers of HAZ metal varied from 0.026 mm to 0.130 μm, total projection of damage area was equal to about 100 % (Table 2). In addition to corrosion pits, local corrosion damage in the form of intercrystalline cracks is found in the fusion zone (Figure 2, *b*). After HFMP treatment of the fusion line, a reduction of the depth of corrosion pits in the HAZ region practically to zero was noted (Table 2); intercrystalline cracks coming to the surface along the line of weld fusion with base metal were revealed (Figure 2, *d*).

Thus, treatment of fusion line by HFMP technology promoted an increase of corrosion resistance of this zone (by corrosion defect size). More precise determination of the origin of intercrystalline cracks in welded joints before and after strengthening requires further studies.

Mechanical testing of two samples of butt welded joints of 25×12 mm cross-section for static short-time tension was performed. Samples failed at a distance from the weld and HAZ through base metal (Figure 4), obtained values of mechanical properties of welded joints correspond to values for base metal ($\sigma_y = 400$ MPa, $\sigma_t = 565$ MPa, $\delta_5 = 27$ %).

Results of fatigue testing of samples of butt welded joint of 15KhSND steel of all the series are given in Figure 5.

Large scatter of experimental data of samples of welded joints in the initial state (Figure 5, curve *1*) is, apparently related to the technology of sample

Table 1. Microhardness distribution from the surface in-depth of HAZ metal in butt welded joints of 15KhSND steel before and after treatment of fusion line by HFMP technology

Sample characteristic, weld number		*l*, mm	Microhardness *HV*0.49
In the initial state	First weld	1.73	192; 201; 210; 192; 168; 182; 192; 185;181
	Second weld		216; 223; 210; 210; 198; 192; 192; 197; 182
After HFMP	First weld	1.80	210; 210; 210; 210; 221; 208; 181; 183; 177
	Second weld		232; 232; 236; 232; 210; 203; 183; 192; 192
Note. *l* — distance from samples surface.			

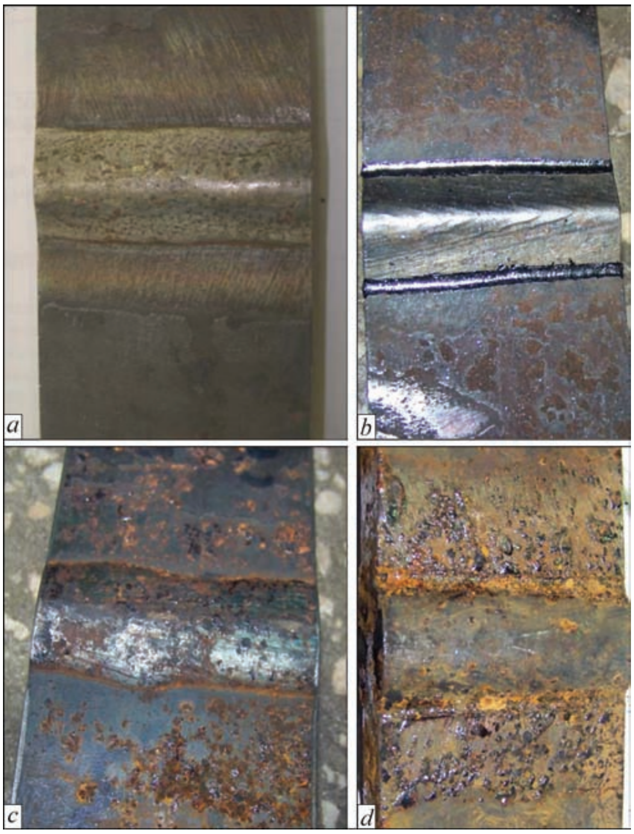

Figure 3. Appearance of samples of butt welded joints from 15KhSND steel in the initial (*a*, *c*) and HFMP strengthened (*b*, *d*) states before (*a*, *b*) and after (*c*, *d*) corrosion testing at high humidity for 1200 h

preparation: as welded joint samples were produced by cutting 600×350 mm plate into blanks for samples of 350×70 mm size, the level of residual stresses in the samples could be different, depending on their position in the plate (edge, middle). Strengthening of welded joints by HFMP technology promoted a significant reduction of experimental data scatter (Figure 5, curve *2*). Cyclic fatigue life of as-strengthened samples (second series) increased more than 40 times, and fatigue strength at $2\cdot10^6$ cycles increased by approximately 46 % (from 187 to 273 MPa). Three strengthened samples failed through base metal at 15–20 mm distance from the weld; and three samples failed along the fusion line. Obtained results (Figure 5, curves *1, 2*) confirm that application of HFMP technology as the method of SPD of metal of the joints near the areas of fatigue damage localization essentially improves fatigue resistance characteristics of butt welded joints in air (without corrosion damage).

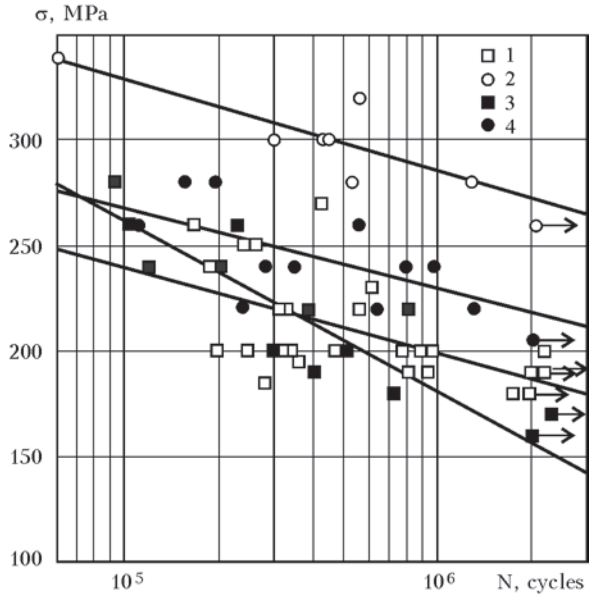

Figure 5. Fatigue curves of butt welded joints of 15KhSND steel: *1, 2* — in the initial state and after HFMP strengthening in air, respectively; *3, 4* — in the initial state and after HFMP strengthening after corrosion testing at high humidity for 1200 h

Soaking of unstrengthened samples of butt welded joints under the conditions of increased humidity for 1200 h (third series) led to lowering of fatigue strength at $2\cdot10^6$ cycles by approximately 16 % (from 187 to 157 MPa) and reduction of cyclic fatigue life in the range of $4\cdot10^5$–$2\cdot10^6$ cycles by 2.5 times (Figure 5,

Table 2. Dimensions of corrosion damage of surface layer of metal of weld and HAZ of butt welded joints of 15KhSND steel after exposure under the conditions of high humidity for 1200 h

Sample characteristic	Dimensions of corrosion damage of surface layers			
	Weld metal		HAZ metal	
	Depth, mm	Degree of damage, %	Depth, mm	Degree of damage, %
In the initial state	0.039–0.104	19	0.026–0.130	100
After HFMP treatment	0.039–0.091	6.3	Within measurement error	

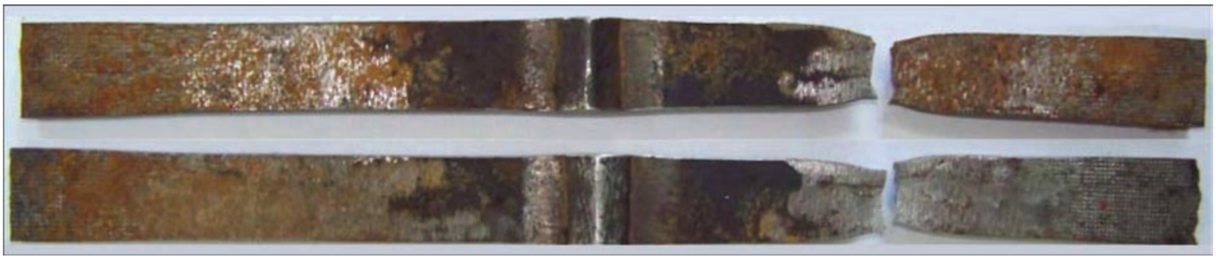

Figure 4. Appearance of welded joint samples after testing for static tension

curve *3*). Corrosive effect resulted in lowering of fatigue strength of HFMP strengthened joints by approximately 20 % (from 273 to 219 MPa) (Figure 5, curve *4*). However, obtained experimental data point to the rationality of HFMP strengthening of butt welded joints at the stage of fabrication in metal structures, which will be exposed to alternating loading and high humidity, as HFMP leads to 39 % increase of fatigue strength at $2\cdot10^6$ cycles (from 157 to 219 MPa) in such joints, and up to 9 times increase of their cyclic fatigue life.

Failure of HFMP strengthened welded joints tested after exposure to high humidity proceeded both through the HAZ and through base metal at 15–60 mm distance from the weld. It should be noted that fatigue strength of HFMP strengthened joints even after soaking in the moisture chamber for 1200 h is 17 % higher than fatigue limit of unstrengthened joints tested in air.

Thus, experimentally obtained results are indicative of high effectiveness of application of HFMP technology to improve fatigue resistance characteristics of welded joints of metal structures, operating under the conditions of simultaneous impact of alternating loading and temperate climate atmosphere (Figure 5, curves *3*, *4*).

It should be noted that additional protection of HFMP strengthened surface layer of metal from direct impact of atmospheric conditions (for instance, due to application of paint and varnish coatings), will, possibly, allow achieving maximum fatigue resistance characteristics of such joints (Figure 5, curve *2*).

Conclusions

1. Metallographic studies showed that HFMP of fusion line of butt welded joints results in intensive deformation (elongation) of grains of weld and HAZ metal. Here, the depth of prastically deformed layer of metal under the groove with considerable changes of grain form (grain form factor K_f = 8–20) is equal to approximately 260–325 μm. It is found that HFMP strengthening of welded joints before exposure to high humidity conditions promotes an improvement of their corrosion resistance: reduction of the depth of corrosion pits and degree of HAZ metal damage from 100 % to practically 0.

2. It was confirmed that HFMP strengthening of the fusion line essentially improves fatigue resistance characteristics of welded joints of 15KhSND steel in air: cyclic fatigue life increases by more than 40 times, and fatigue strength at $2\cdot10^6$ cycles increases by 46 %.

3. High effectiveness of HFMP technology application to improve fatigue resistance characteristics of welded joints of metal structures operating at simultaneous action of alternating loading and temperate climate atmosphere was established. HFMP strengthening of butt welded joints of 15KhSND steel before exposure to high humidity for 1200 h leads to increase of cyclic fatigue life up to 9 times, depending on the levels of applied stresses and 39 % increase of fatigue strength at $2\cdot10^6$ cycles.

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