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IMPACT OF HIGH-FREQUENCY PEENING AND MARINE ATMOSPHERE ON THE CYCLIC LIFE OF T-WELDED JOINTS WITH SURFACE FATIGUE CRACKS

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The results of investigations of the efficiency of application of high-frequency mechanical peening technology to increase the residual life of T-welded joints of 15KhSND steel with surface fatigue cracks of 2–20 mm length and corrosion damage typical for structures after long-term service in the conditions of marine climate are presented. The long-term impact of marine atmosphere, which is typical for coastal regions of Ukraine, on the state of the surface of joints, was simulated by exposure of the samples in the salt spray chamber KST-1 for 1200 h. It was shown that surface cracks and corrosion damage significantly reduce the residual cycle life of welded joints. It was experimentally found that HFMP strengthening of T-welded joints with surface fatigue cracks of 5–7 mm length (depth is up to 1.6 mm) and characteristic corrosion damage increases their residual cyclic life to the level of welded joints with corrosion damage, strengthened by high-frequency mechanical peening at the stage of manufacturing. It is shown that in the presence of fatigue cracks of 20 mm length (about 6 mm depth), their residual life is reduced by up to 10 times, and the use of high-frequency mechanical peeening technology for such joints does not increase the cyclic life and is ineffective. 14 Ref., 2 Tables, 5 Figures.

Keywords: T-welded joints, corrosive medium, fatigue, accelerated corrosion tests, salt spray, high-frequency mechanical peening, increase in cyclic life

Technology of high-frequency mechanical peening (HFMP), also known as ultrasonic impact treatment, is widely applied to increase the fatigue resistance characteristics of welded joints of metal structures [1−6]. This technology is recommended for application to welded metal structures, operating in marine climate (bridges, overpass bridges, off-shore platforms, etc.) [7−11]. However, all the experimental data given in the above-mentioned works, were obtained under laboratory conditions in air (without corrosion impact) on samples of welded joints, which were strengthened by HFMP technology directly after welding. It is obviously believed that these structures are protected from the impact of environmental climatic factors (from corrosion) by lacquer-paint coatings. During long-term operation, however, mechanical damage, cracking and delamination of the lacquer-paint coatings can occur. This leads to the fact that the welded elements of the structures are exposed not only to alternating loading, but also to corrosive attack. In works [12, 13] the efficiency of HFMP technology application to welded structures with the specified level of accumulated fatigue and corrosion damage was studied. It is experimentally established that strengthening by HFMP technology of butt welded joints of 15KhSND steel after prior cyclic loading ($2\cdot10^6$ cycles) and exposure to the impact of neutral salt spray for 1200 h (long-term impact of marine atmosphere was simulated) leads to 10 times increase of their cyclic life, and endurance limit after $2\cdot10^6$ cycles increases by 25 % [12]. Application of HFMP technology allows also a ten times increase of cyclic life of butt welded joints with the specified level of accumulated fatigue and corrosion damage, which are characteristic for metal structures after long-term exposure to moderate climate atmosphere of the central regions of Ukraine [13]. However, there is still no data on the effectiveness of application of HFMP technology to welded joints of metal structures, which have surface fatigue cracks of small depth, and characteristic corrosion damage, as a result of long-term service in marine climate typical for the coastal regions of Ukraine.

The objective of this work is studying the residual cyclic life of T-welded joints with surface fatigue cracks and corrosion damage, characteristic for welded metal structures after long-term service in marine climate, without and after application of HFMP technology.

Material and investigation procedure. Experimental studies were conducted on specimens of

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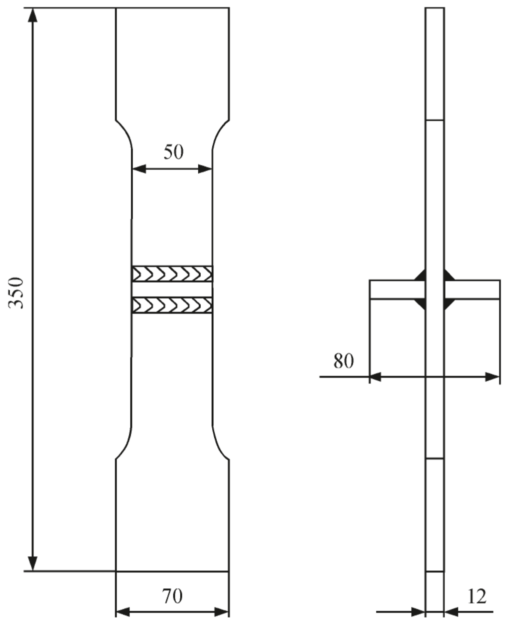

Figure 1. Shapes and geometrical dimensions of specimens of T-welded joint

T-welded joints of low-alloyed 15KhSND steel (σ_y = = 400 MPa, σ_t = 565 MPa), which is widely applied for fabrication of elements of metal structures in long-term service (for instance, in span structures of railway and road bridges), has higher strength, is readily weldable, weather-resistant and serviceable in the temperature range from minus 70 °C up to plus 45 °C.

The blanks for welded joint specimens were cut out of hot-rolled plates 12 mm thick of category 12 in the rolling direction. T-welded joints were produced by manual arc welding with electrodes of UONI 13/55 grade the transverse stiffeners (also from 15KhSND steel) to blanks of 350×70 mm size by fillet welds from both sides. The root (first weld) was made by 2 mm electrodes, the second weld was formed by 4 mm electrodes. The shape and geometrical dimensions of specimens of T-welded joints are given in Figure 1. Specimen thickness is due to wide application of 12 mm thick rolled stock in engineering welded metal structures, and 50 mm width of the working part was selected, proceeding from testing equipment capacity.

All the fatigue studies were conducted in servohydraulic testing machine URS-20 with cycle asymmetry $R_\sigma = 0$ and 5 Hz frequency at regular loading. At the first stage, fatigue testing was performed at maximum values of applied cycle loads of 180 MPa with the purpose of initiation and development of fatigue cracks of a small size on the specimen surface. This level of applied maximum loads is close to endurance limit of these joints on the base of $2\cdot10^6$ cycles of stress alternation [14]. To avoid complications, associated with reliable determination of fatigue crack depth, the crack reaching the specified size of 5 to 30 mm on the specimen surface was selected as the criterion of completion of fatigue testing during investigations. During these tests, the specimens in the weld zone were lubricated by indicator fluid, which consisted of kerosene and toner. After formation of a crack of specified size on the specimen surface (all the cracks formed on the line of weld metal transition to base metal), the remains of indicator fluid were removed by blowing compressed air. The indicator fluid was not used at further testing of the specimens that allowed determination of geometrical dimensions of initial cracks on welded joint fractures. After development of cracks on the specimen surface to the specified size, accelerated corrosion testing was conducted under the conditions, which simulate the impact of moderate climate atmosphere of the coastal regions of Ukraine. As the coastal regions are characterized by presence of chlorides in the environment, their long-term impact on the welded joints was simulated by specimen exposure to neutral salt spray for 1200 h, i.e. the specimens of welded joints were exposed in salt spray chamber KST-1 at the temperature of (35 ± 2) C at spraying of sodium chloride solution for 15 min every 45 min. Sodium chloride concentration in the solution was (50 ± 5) g/dm^3; pH was from 6.5 to 7.2; density was 1.03 g/cm^3. Electric conductivity of distilled water for preparation of sodium chloride solution is not more than 20 μOhm/cm at the temperature of (25 ± 2) °C. Thus, as a result of prior fatigue and accelerated corrosion testing the test specimens had damage characteristic for welded joints of metal structures after long-term service at alternating loading in moderate climate of the coastal regions of Ukraine.

When preparing for fatigue testing, the specimens with surface fatigue cracks and corrosion damage, their gripping portions were scraped again to remove corrosion damage. Scraping of the weld zone from corrosion products to metal luster was not performed. One part of the specimens was left in the unstrengthened state, and the second was strengthened by HFMP technology. Strengthening of welded joints by HFMP technology was performed by USTREAT-1.0 instrument, in which the manual compact impact tool with piezoceramic transducer is connected to ultrasonic generator with output power of 500 W. At treatment of welded joints by HFMP technology, surface plastic deformation was applied not only to the fusion line with the fatigue crack, but to all the four lines of weld metal transition to base metal of the T-joint. Single-row four-striker attachment with striker diameter of 3 mm was used as the strengthening device. Strengthening was performed without prior scraping of the surface to remove corrosion products.

Thus, fatigue testing was conducted on two series of specimens:

- specimens of T-welded joints with surface fatigue cracks 5–30 mm long and corrosion damage (first series);
- specimens of T-welded joints with surface fatigue cracks 5–30 mm long and corrosion damage, which were strengthened by HFMP technology (second series).

Experimental studies of residual fatigue life of these welded joints were performed up to complete breaking of the specimens or exceeding the test base of $2\cdot10^6$ cycles of stress alternation at regular loading with cycle asymmetry $R_\sigma = 0$ and 5 Hz frequency.

Test results. Description of corrosion damage which occurred in T-welded joints after corrosion testing for 1200 h in salt spray chamber KST-1 was given earlier in work [14].

Results of fatigue testing of T-welded joints of 15KhSND steel with fatigue cracks without HFMP strengthening (first series) are given in Figure 2 and Table 1. Figure 2 also shows the data on fatigue resistance of T-welded joints in the initial and HFMP strengthened states after corrosion testing for 1200 h in salt spray chamber KST-1, obtained in [14]. Table 1 gives the dimensions of surface cracks, which were determined after fatigue testing, when studying the fracture surfaces of specimens, using the indicator fluid. Fractures of T-joint specimens with surface cracks and corrosion damage are given in Figure 3. One can see that the proposed procedure allows accurately determining the geometrical dimensions of the initial crack on the fractures after specimen breaking. Despite the fact that all the fatigue cracks initiated in the fusion zone in the specimen center, the coefficient of compression of the surface crack (crack depth to half-width ratio) in them is in the range from 0.350 to 0.825. We believe that this is related to crack propagation in different (by magnitude and gradient) fields of residual welding stresses, as a result of successive performance of four fillet welds by manual arc welding when manufacturing the specimens. Geometrical dimensions of the initial cracks were recorded right after specimen fracture (Table 1). However, because of rapid oxidation of the fracture surface, some of the cracks shown in Figure 3 appear to be larger than their real dimensions. All the specimens broke along the fusion line, which had an initial fatigue crack. The residual cyclic life of T-welded joints of 15KhSND steel with surface cracks of up to 1 mm depth after corrosion testing in neutral salt spray for 1200 h, is 1.5 to 2.0 times lower than the fatigue life of welded joints in as-welded state after respective corrosion

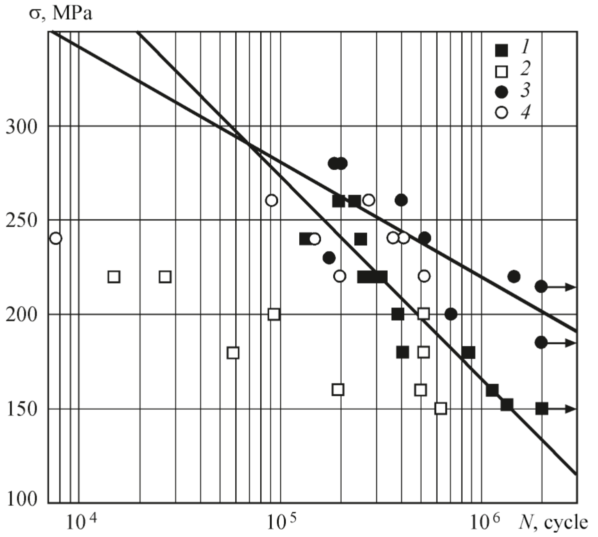

Figure 2 Experimental data of fatigue testing of T-welded joints of 15KhSND steel: *1* — in the initial state after soaking for 1200 h in KST-1 chamber [14]; *2* — after testing up to formation of surface fatigue cracks and soaking for 1200 h in KST-1 chamber; *3* — after HFMP strengthening and soaking for 1200 h in KST-1 chamber [14]; *4* — after testing up to formation of surface fatigue cracks, soaking for 1200 h in KST-1 chamber and subsequent strengthening by HFMP technology (solid lines are regression lines of data of *1* and *3*)

Table 1 Cyclic life of T-welded joints with corrosion damage and surface fatigue cracks

Specimen number	l_{cr}, mm	h_{cr}, mm	N_{cr}, cycles	σ_{max}, MPa	$N_{cr}^{unstrength}$, cycles	Note
2290	8	3.3	1531200	160	192900	Breaking along the fusion line
2291	5	0.9	1345200	150	630600	Same
2292	2	0.5	1950000	180	517700	»
2293	11	2.2	1136000	200	93400	»
2294	20	3.5	1353200	220	26700	»
2295	20	5.8	804800	220	14800	»
2296	5	1.0	1415300	200	516800	»
2297	15	5.8	1610900	180	58300	»
2298	9	2.1	1866400	160	500400	»

Note. l_{cr} and h_{cr} — crack length and depth before corrosion testing, respectively; N_{cr} — cyclic life up to initiation of a crack of specified length at maximum applied loads of 180 MPa; σ_{max} — maximum cycle stresses; which were applied to the specimen with a crack after corrosion testing for 1200 h in KST-1 chamber; $N_{cr}^{unstrength}$ — residual cyclic life of a specimen with a fatigue crack of the specified length and corrosion damage.

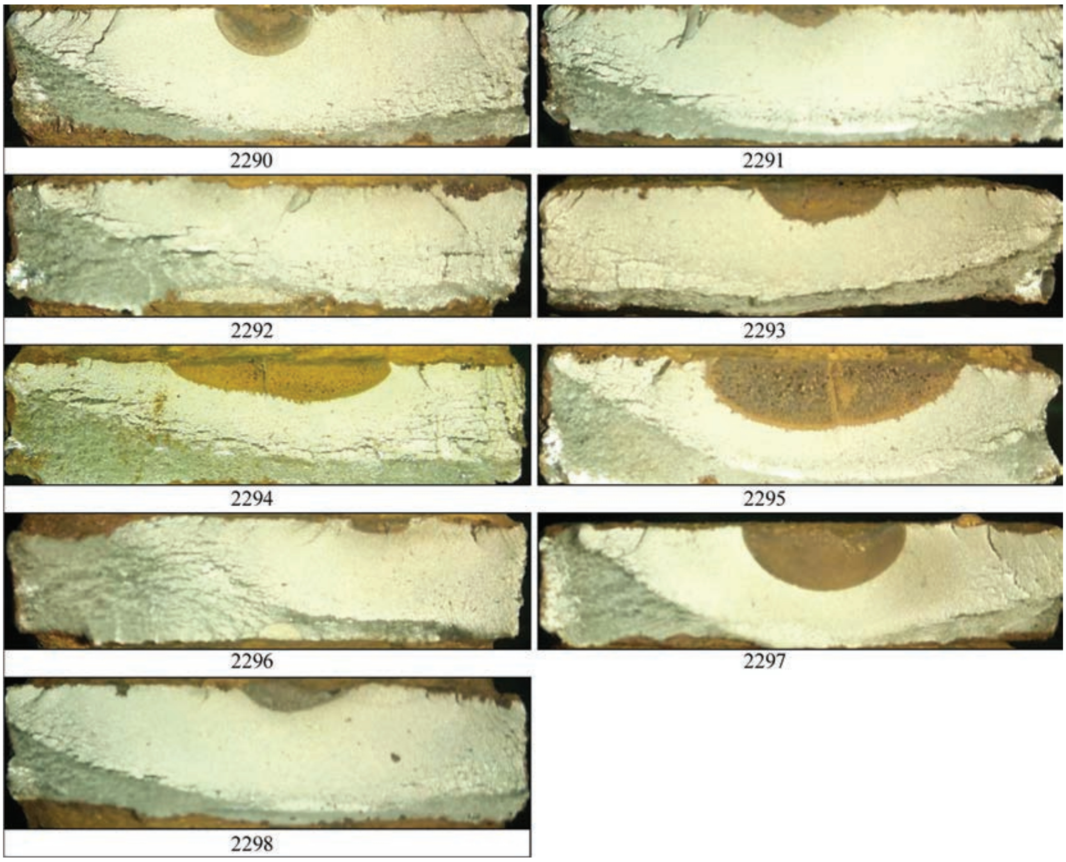

Figure 3. Fatigue fractures of specimens of T-welded joints of 15KhSND steel with surface fatigue cracks, which were not strengthened by HFMP after corrosion testing for 1200 h in KST-1 chamber (see Table 1)

testing. With increase of the initial crack depth, the residual life of the joints becomes much lower (Table 1, Figure 2). At more than 3.5 mm depth of the fatigue crack, the residual life of the joints decreases 10 times.

Residual cyclic life of T-joints of 15KhSND steel after formation of surface fatigue cracks, soaking for 1200 h in the salt spray chamber KST-1 and subsequent HFMP is given in Table 2, and Figure 2. Table 2 also presents the dimensions of surface cracks, which

Table 2 Cyclic life of T-welded joints with corrosion damage and surface fatigue cracks after their strengthening by HFMP technology

Specimen number	l_{cr}, mm	h_{cr}, mm	N_{cr}, cycles	$\sigma_{cr}^{strength}$, MPa	$N_{cr}^{strength}$, cycles	Note
2197	10	3.0	826700	240	147900	Fracture along fusion line
2198	5	1.6	804100	240	407600	Same
2199	20	5.9	770400	240	7700	»
2200	5^{**}	–	481200	260	275500	Fracture through the base metal at 55 mm distance from the weld
2201	12	2.4	760100	260	91700	Fracture along fusion line
2202	7 $+3^{*}$	1.6 $+0.6^{*}$	1281700	240	368200	Same
2203	$5+10+5^{*}$	$0.5+1.8+0.6^{*}$	452800	220	199300	»
2204	7^{**}	–	764300	220	522800	Fracture through the base metal at 55 mm distance from the weld

Note. l_{cr} and h_{cr} – crack length and depth before corrosion testing, respectively; $N_{cr}^{strength}$ — cyclic life up to initiation of a crack of specified length; $\sigma_{cr}^{strength}$ are maximum cycle stresses, applied to a specimen with a crack after corrosion testing for 1200 h in KST-1 chamber and strengthening by HFMP technology; $N_{cr}^{strength}$ — residual cyclic life of a specimen with a crack of specified length and corrosion damage after strengthening by HFMP technology; * — specimens with several separate surface cracks along one fusion line; ** — specimens, in which crack length was established by kerosene method.

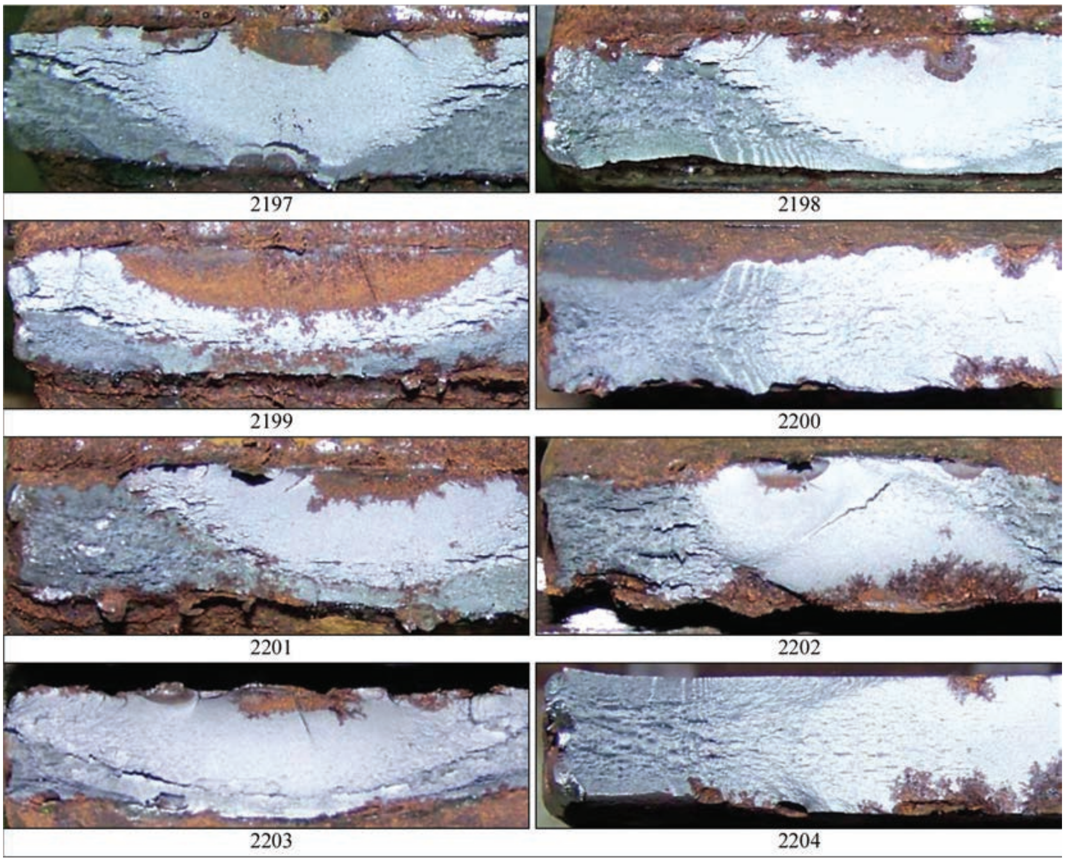

Figure 4. Fatigue fractures of specimens of T-welded joints of 15KhSND steel with surface fatigue cracks, which were strengthened by HFMP after soaking for 1200 h in KST-1 chamber (see Table 2)

were determined after fatigue testing when studying the fracture surfaces of specimens, due to application of indicator fluid. Geometrical dimensions of the initial cracks were recorded right after specimens breaking (Table 2). However, because of fast oxidation of the fracture surfaces, some cracks shown in Figure 4, appear to be larger than their real dimensions. Fracture of HFMP strengthened specimens occurred predominantly along the fusion line (Figure 5). Two specimens (No.2200 and No.2204), which had fatigue cracks 5–7 mm long (dimensions are determined by kerosene method during crack growth), after strengthening by HFMP broke through the base metal at a distance from the weld, as a result of new crack initiation from corrosion cavities in the hot-rolled surface layer of the metal (Figures 4, Figure 5). This did not allow reliable determination of the depth of the initial cracks. Considering the data of Table 1 and Table 2, however, we can state that at the moment of strengthening by HFMP, their depth did not exceed 1.6 mm. It is experimentally established that the effectiveness of application of HFMP technology, in order to increase the cyclic fatigue life, is actually determined by the geometrical dimensions of the fatigue crack before treatment. Thus, strengthening by HFMP technology of T-joints with surface fatigue cracks 5–7 mm long (of up to 1.6 mm depth) significantly increases their cyclic life. The scatter of experimental data of such joints is within the data scatter for joints strengthened by HFMP at the manufacturing stage (without accumulation of fatigue damage) and subsequent soaking in KST chamber for 1200 h (Figure 2). After HFMP strengthening, the residual cyclic life of the joints with surface cracks of 10–12 mm length (1.8 to 3.0 mm depth) is on the level of cyclic life of unstrengthened welded joints after soaking in KST chamber for 1200 h, i.e. it is 2–3 times lower than that of HFMP strengthened joints at the manufacturing stage. Application of HFMP technology to welded joints, which

Figure 5 Specimens of T-welded joints of 15KhSND steel with surface fatigue cracks, which were strengthened by HFMP after soaking for 1200 h in KST-1 chamber, shown after fatigue testing

contain fatigue cracks of approximately 6 mm depth, is ineffective (Table 2, Figure 2).

Thus, the high effectiveness of application of HFMP technology for improvement of cyclic life was established for T-welded joints of metal structures, which have surface fatigue cracks of up to 5–7 mm length and characteristic corrosion damage, as a result of long-term service under the conditions of moderate climate of the coastal regions of Ukraine.

Conclusions

1. We performed experimental studies of the residual life of T-welded joints of 15KhSND steel with surface fatigue cracks and corrosion damage, characteristic for metal structures after long-term service in marine climate. Long-term impact of marine atmosphere, which is characteristic for the coastal regions of Ukraine, was simulated by joint exposure for 1200 h in salt spray chamber KST-1. It is confirmed that with increase of the initial crack length, the residual life of joints with corrosion damage becomes smaller. Residual cyclic life of T-welded joints with surface cracks 2–5 mm long (up to 1 mm depth) after corrosion testing in neutral salt spray for 1200 h is 1.5 to 2.0 times lower than the fatigue life of welded joints in as-welded condition after the respective corrosion testing, and residual life of joints with 20 mm fatigue cracks (more than 3.5 mm depth) decreases 10 times.

2. Studied was the application of HFMP technology to improve the residual life of T-welded joints of 15KhSND steel with surface fatigue cracks and corrosion damage, characteristic for metal structures after long-term service in moderate climate of the coastal regions of Ukraine. It was found that strengthening by HFMP technology of T-welded joints with surface fatigue cracks of up to 5–7 mm length (up to 1.6 mm depth) raises their cyclic life to the level of HFMP strengthened welded joints at the manufacturing stage. After strengthening the welded joints with surface fatigue cracks of 10 – 12 mm length (1.8 to 3.0 mm depth) their residual life is on the level of cyclic life of unstrengthened welded joints, i.e. it is 2–3 times lower than that of HFMP strengthened joints at the manufacturing stage. It is shown that application of HFMP technology to welded joints with fatigue cracks of approximately 6 mm depth does not lead to increase of their cyclic life and is inefficient.

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