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STATE-OF-THE-ART OF METHODS FOR IMPROVEMENT OF CORROSION RESISTANCE AND CORROSION FATIGUE RESISTANCE OF WELDED JOINTS (REVIEW)

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To improve the service reliability of products and welded structures in the conditions of corrosive environment, the methods of surface plastic deformation of metal are applied, which impart the physical-mechanical properties to the hardened layer, differed from the base metal. The technical progress contributes not only to the development of new methods of surface plastic deformation (for example, surface fusion using a nanopulsed laser), but also to the continuous improvement of conventional methods (shot blasting, pressure treatment, etc.), the efficiency of which was proved in practice. The aim of this review is to evaluate the current state of use of surface plastic deformation methods to increase the corrosion fatigue resistance and durability of steels and welded joints. The analysis of literature data showed that the experimental investigations of recent years are mainly devoted to the determination of efficiency of hardening the stainless steels and their joints applying these methods for subsequent application in such areas as medicine (implants), nuclear power engineering (reactors) and shipbuilding. For the treatment of welded metal structures, the most promising is ultrasonic impact treatment due to compactness and mobility of the equipment, ecological compatibility of the technological process, high efficiency, capability of strengthening the welded joints in any spatial positions in the field conditions. 37 Ref., 4 Figures.

Keywords: *welded joint, corrosion, surface plastic deformation, ultrasonic impact treatment, corrosion fatigue, corrosion resistance*

The service life of a large part of welded metal structures (bridges, overpasses, stationary offshore platforms, antenna-mast constructions, cranes, frames of rolling stock carriages, etc.) is determined by the fatigue resistance of their welded assemblies and components. The corrosive effect from the environment leads to a decrease in the characteristics of fatigue resistance of the base metal and welded joints, and, as a result, promotes a premature corrosion-fatigue fracture. To improve the service reliability of products and structures, the advanced welding technologies are introduced, new welding materials are applied, modern coatings are used, etc. The application of these measures, as a rule, is not sufficient for a significant increase in their service life, therefore, in practice, to increase the fatigue resistance of base metal and welded joints under the influence of corrosive environment the different methods of surface plastic deformation (SPD) of the metal are applied. The SPD methods, such as shot blasting, running-in by balls and rollers, pneumatic hammer treatment, hydraulic shot blasting, inertial-dynamic hardening, explosion treatment, etc. have proved to be efficient. Despite the considerable volume of publications on the establishment of efficiency in application of SPD methods and the experience of their use in practice [1–4], the world research centers continue to carry out investigations on this topic. This is associated with the fact that a constant improvement of technologies (equipment, consumables) and the materials, which are subjected to hardening, expands the scope of application for SPD methods.

Increase in corrosion resistance and resistance to corrosion fatigue of metals and alloys applying SPD methods. Over the years in the course of investigations it was established that SPD methods contribute to change in the structure of the surface layer of metal, increase in hardness and wear resistance, inducing the residual compressive stresses, increase in resistance to corrosion fatigue and change in roughness of the surface. The publications of the recent years are devoted to investigation of efficiency of conventional SPD methods (shot blasting, grinding and treatment by a pneumatic hammer) depending on technological parameters of surface hardening, as well as on investigation of quite new technologies (for example, surface fusion using a nanopulsed laser or high-power pulsating electron beam) [5–17].

In the works [6–9] the results of investigations of shot blasting treatment (ST) of the surface of specimens of base metal of stainless steels are given for increase of their corrosion resistance. The results of investigations of corrosion resistance of hardened specimens are given depending on technological parameters of treatment: type of shot (steel, ceramic) and size of shot (from 125 to 850 μm), working air pressure, treatment time, number of surface treatments (one or two) and intensity of treatment. It was established that ST improves the hardness and wear resistance of specimens, but, as a rule, it leads to decrease in corrosion resistance of stainless steels. This is connected with increase in the effective surface area of corrosion-mechanical losses of the material due to increase in surface roughness after ST. In order to increase the corrosion resistance of base metal, it is proposed to apply the additional measures for the surface passivation: deposition of a thin hydroxyapatite film, nitriding, grinding to the depth of 10–15 μm. It was shown that application of ST leads to increase in resistance to corrosion fatigue. In the work [6] it was established that the limit of the endurance margin based on $2\cdot10^7$ cycles of stress changes in specimens of steel AISI316L in Ringer's solution after ST is 4 % lower than that after compression (deformation) in hot state, but it is 55 % higher than in the initial state (Figure 1). The deposition of a hydroxyapatite film additionally increases the limit of the endurance margin of specimens in Ringer's solution by 4.4 % after ST and by 6.3 % after deformation in a hot state.

In the works [9–11] the data of corrosion resistance of specimens of stainless steels after application of the technology of high-frequency mechanical peening (HMP), known as ultrasonic impact treatment (UIT) in the foreign literature, are given. It was established that UIT improves their corrosion resistance due to structural changes in the surface layer of the metal, increase in microhardness and formation of a uniform oxide film enriched in chromium. It is shown that as a result of UIT of steel AISI321 the refining of structure to nanosizes occurs in a thin surface layer of metal: in the course of deepening to 30 μm from the surface being treated, the grain size increases gradually from 10 to 60 nm. It is noted that despite a more significant increase in martensite after UIT, and, consequently, the increase in galvanic effect between austenite and martensite in stainless steels, the resistance of general and localized corrosion of specimens after UIT is higher as compared to the base metal and specimens, hardened applying ST.

In the work [12] the efficiency of applying surface mechanical grinding (SMG) for increasing the corrosion resistance of specimens of stainless steel AISI304 was investigated depending on such technological parameters of treatment as diameter of the balls (2, 5 and 8 mm), and the time of treatment (15, 30 and 45 min).

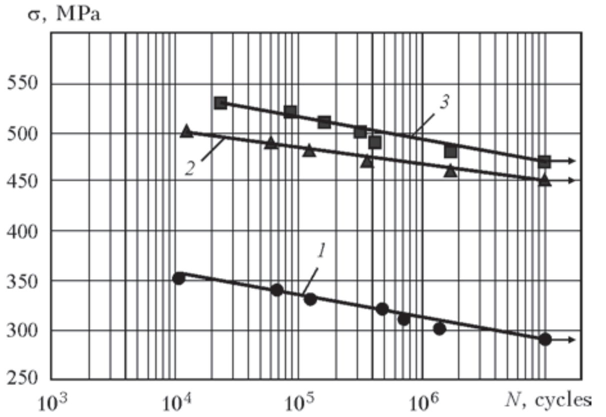

Figure 1. Fatigue curves of specimens of steel AIS1316L in Ringer's solution: *1* — in initial state; *2* — after hardening by shot blasting treatment; *3* — after compression (deforming) in a hot state [6]

The SMG technology represents a mechanical surface treatment with steel balls over the preset time in the special vacuum chamber mounted on the vibrating table. It was shown that roughness of specimen surface after SMG increases with increase in diameter of the applied balls and almost does not depend on the time of treatment. It was found that only during treatment with balls of 2 mm diameter, the corrosion resistance of specimens hardened applying SMG in NaCl solution negligibly exceeds the strength of unhardened specimens.

In the work [13] the results of experimental investigations of efficiency of application of quartz shot blasting (in fact sandblasting) and polishing to improve the corrosion resistance of specimens of stainless steel AISI316LVM, widely used in medicine, are presented. It is shown that a higher corrosion resistance is in the specimens after polishing and passivation of the surface during 60 min holding in 20 % solution of NHO_3. It was found that, despite the maximum roughness, the corrosion resistance of specimens after quartz shot blasting during 120 s and the subsequent passivation of the surface is almost not inferior to the specimens after polishing and passivation. High roughness and corrosion resistance make this treatment promising for using in medicine to improve the corrosion resistance of implants of steel AISI316LVM.

In the works [14, 15] the influence of plastic deformation (pressure treatment) on corrosion resistance of stainless steels was investigated. It was established that with increase in the deformation degree (reduction in thickness) of the rolled products from 17 to 47 %, the hardness, yield strength and corrosion resistance are increased. The authors of the work [15] showed that during manufacture of pipes according to the conventional technology (hot-rolled products, deformation degree is 68 %), the rate of pitting corrosion is 3–4 times higher than after the proposed technology of hardening (cold-rolled metal, deformation degree is 75–78 %). The drawbacks of the standard document ASTM G-48, which regulates the tests on resistance to pitting corrosion at the temperature of 40 °C, were mentioned. It is shown that increase in temperature from 40 to 50 °C increases the rate of corrosion by hundreds of times. It is noted that the subsequent sand blasting does not lead to change in mechanical properties, but it significantly reduces the corrosion resistance of the material due to increase in roughness of the surface.

In the work [16], the efficiency of the fusion of steel AISI304L surface using nanopulsed laser was investigated. It was established that this treatment leads to increase in surface roughness (due to spatter of molten metal from pulsating laser), formation of an oxide film with high chromium content, the replacement of martensite with δ-iron and stretching of grains towards the treatment surface. The abovementioned changes in the surface layer of metal contribute to increase in corrosion resistance.

In the work [17], the use of pulsating high power electron beam (PHPEB) was investigated with the aim of increasing the corrosion and wear resistance of steel FV520B (chromium content is 13.0–14.5 %). The parameters of equipment for PHPEB are the following: voltage is 27 kV, maximum current is up to 10 kA, pulse time is 2.5 μs. It is shown that with increase in the number of pulses from 1 to 25, the average grain size in the surface layer of metal does not exceed 2 μm, but the thickness of this layer is only 4 μm. After treatment by 25 pulses, the corrosion rate decreases significantly, and the wear resistance three times increases.

Improvement of corrosion resistance and resistance to corrosion fatigue of welded joints of metal structures applying SPD methods. The application of sufficiently new SPD methods (high-power pulsed electron beam and surface fusion using nanopulsed laser) for treatment of welded joints of engineering metal structures is not possible at this stage of their development. During hardening of the structures, the preference is given to the SPD methods, which allow performing treatment of welded elements of a complex geometric shape, treatment of longitudinal welds, as well as site welds in the field conditions. The most effective among them are the methods which provide the maximum reduction in stress concentration at the transition from the weld metal to the base metal, the substantial relaxation of residual welding tensile stresses and inducing the residual compressive stresses: grinding, ST, treatment with pneumatic hammer and UIT.

In the works [18, 19], the experimental data are presented on increase in the characteristics of fatigue resistance of welded joints applying grinding the fusion line in the air and under water, respectively. The authors of the work [18] established that grinding of the fusion line increases the limit of endurance margin of welded joints of stainless steels on the basis of 10^7 cycles of stress changes by 109 % (from 110 to 230 MPa) and by 63 % (from 86 to 140 MPa), respectively, in air and in 3 % solution of NaCl. Moreover, the cyclic life of welded joints increases in air by up to 50 times, and by up to 10 times in the corrosive environment. In the work [19] it was shown that the limit of endurance margin of welded joints of low-alloyed steel on the basis of $2\cdot10^6$ cycles of stress changes is increased by 20 % after grinding of the fusion line, by 35 % after UIT, and by 61 % after grinding with subsequent UIT. It is noted that the level of induced residual compressive stresses after UIT is 3 times higher than after grinding.

In the works [20, 21] the efficiency of applying ST to increase the resistance of butt welded joints of stainless steels to pitting corrosion and stress corrosion cracking, respectively, is considered. In the work [20], the welded joints were produced both by the electric arc welding (EAW), as well as by the laser welding (LW). The tests on corrosion resistance were carried out in the salt fog chamber (5 % NaCl solution) with a periodic inspection after 24, 48, 72, 120, 240, 480, 720 and 1000 hours. It is shown that in the joints produced by EAW, the pitting corrosion occurs most intensively in the heat-affected zone (HAZ), the depth of pittings reaches 20–40 μm. After ST hardening, the depth of pittings does not exceed 5–10 μm. In the joints produced by LW, the pittings were formed along the fusion line, reaching 30 μm in depth. After application of ST, the pittings were not revealed even at 1000 h of exposure in 5 % solution of NaCl, i.e. the complete protection against corrosion (R_p10) was achieved in accordance with PN-EN ISO 10289:2002. In the work [21], the resistance to stress corrosion cracking of specimens produced by plasma welding was evaluated according to the corrosion susceptibility coefficient of welded joints on the basis of comparing the areas of diagrams of specimens tension (by the value of the spent work) in the air and in 3.5 % solution of NaCl. It was established that the highest resistance is in welded joints after shot blasting at the air pressure of 0.4 MPa. It is shown that with decrease or increase in air pressure, the corrosion resistance of the joints deteriorates.

In the work [22] it is proposed to increase the characteristics of resistance to corrosion fatigue of welded T-joints of steel 12Kh18N10T using a pneumatic hammer with a ball-pin hardener (BPH). It was established that in hardening of weld and HAZ of up to 15 mm width, the limit of endurance margin of welded joints on the basis of 10^7 cycles of stress changes is increased by 25 and 27 %, respectively, in air and in the synthetic sea water. It is shown that sea water reduces the limit of endurance margin of welded joints based on 10^7 cycles as compared to the air tests by 16.7 and 15.3 %, respectively, in the initial and hardened states (Figure 2).

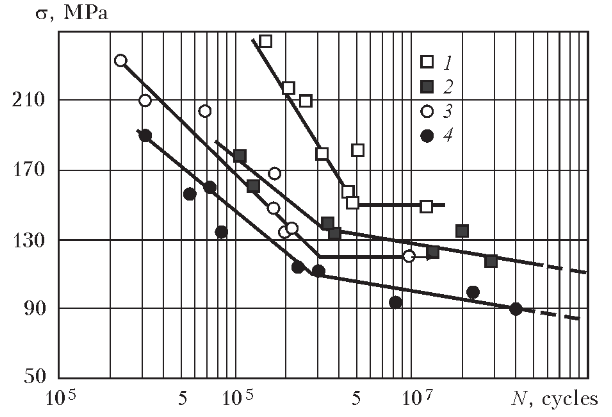

Figure 2. Fatigue curves of welded T-joints of steel 12Kh18N10T: *1, 2* — after applying BPH in air and in synthetic sea water, respectively; *3, 4* — in initial state after welding in air and in synthetic sea water, respectively [22]

In foreign and domestic papers of the recent years, the influence of UIT on corrosion resistance and corrosion fatigue of welded joints is ever increasingly investigated [19, 23–27]. At first, this is connected with the fact that within many years of investigations the basic regularities of improvement of the fatigue characteristics of welded joints in air (without influence of corrosive environment) depending on the strength class of steel, type of welded joint, characteristics of the loading cycle, etc. applying the UIT technology [28–35] have been already established. Secondly, this is facilitated by the compactness and mobility of equipment, environmental cleanness of the technological process of treatment (as compared to grinding, sandblasting and shot blasting), ability to perform hardening of welded joints in any spatial positions, in the field conditions and in some cases under water as well [19].

Thus, in the work [23], the results of fatigue tests of pipe steel welded joints in air and in corrosive environment (10 % solution of NaCl + 10^{-3}–10^{-2} M $Na_2S_2O_3$) in the initial state and after UIT are given. It is shown that as a result of UIT, the radius of transition from weld to HAZ is increased by 1550 %, the angle of weld inclination is reduced by 50 %, the microhardness is increased by 33 %, the structure is refined, the level of residual welding tensile stresses is reduced. In the corrosive environment these factors contribute to twice increase in the cyclic life of welded joints.

In the work [24] the efficiency of application of UIT and laser treatment was evaluated to improve the resistance of corrosion fatigue of butt welded joints of steel 15G2FB. To UIT hardening the fusion line and HAZ of 10–15 mm width were subjected. It is shown that sea water reduces the limit of endurance margin based on $2\cdot10^7$ cycles of stress changes of welded joints in the initial state by 42.8 %, and in the hardened state — by 41.2 %. It was established that the limit of endurance margin of welded joints based on $2\cdot10^7$ cycles of stress changes as a result of UIT in air is increased by 20 % (from 140 to 170 MPa), and in synthetic sea water by 25 % (from 80 to 100 MPa). The laser treatment did not lead to increase in characteristics of fatigue resistance of welded joints. It is noted that fracture of the hardened UIT specimens in sea water occurred far from the fusion line.

In the work [25] the possibility of applying UIT to improve the characteristics of fatigue resistance, microhardness and corrosion resistance of specimens of butt welded joints of stainless steel 304 were investigated. It was established that the limit of endurance margin of butt welded joints based on of $4\cdot10^5$ cycles as a result of UIT, is increased by 29 % (from 225 to 290 MPa). In this case, the depth of the plastically deformed metal layer (visible change in the grain structure) does not exceed 100 μm. It is shown that hardening by UIT twice increases the hardness of the metal of the fusion line. It was established that corrosion resistance in solution of 3.5 % NaCl of the welded joints, hardened applying UIT, is higher than that of unhardened joints and it is at the base metal level. The corrosion rate of the joints, hardened applying UIT, (0.0033–0.0061 mm/year) is at the level of the base metal (0.0038 mm/year), which is significantly lower than the corrosion rate of welded joints in the initial state (0. 0118–0.0323 mm/year).

In the work [26], the efficiency of hardening of transverse welds of 127 mm diameter pipes of low-alloyed steel A106-B operating in the range of temperatures of 25–300 °C, applying UIT, was investigated [26].

It is shown that as a result of UIT, the microhardness of the fusion line metal was increased by 24 %, the residual welding tensile stresses decreased by 66 % and the corrosion rate in the 10 % solution of NaCl + 10^{-3}–10^{-2} M $Na_2S_2O_3$ decreased by 46 %. Reduction in the corrosion rate of the fusion line metal after UIT as compared to the base metal and weld metal is associated with the bainitic structure, improvement of grains and reduction of residual welding stresses. The increase in the cyclic life of specimens cutout from the preliminary hardened pipe was not observed. This

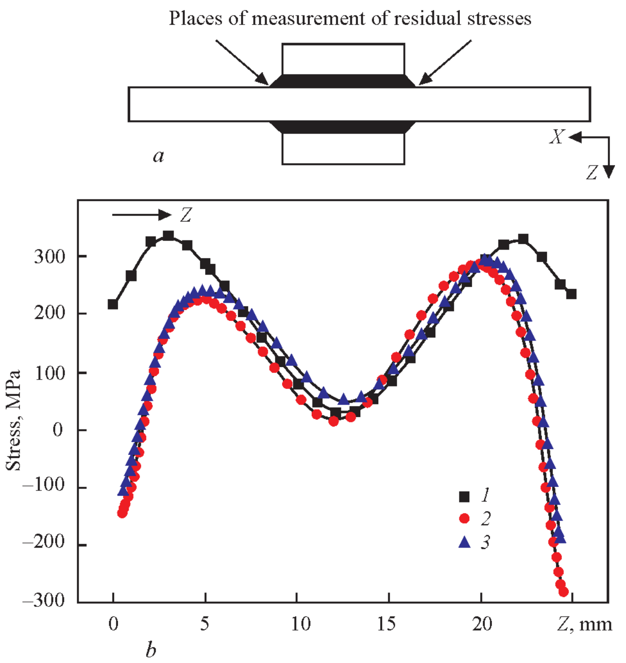

Figure 3. Schematics of measuring points (*a*) and diagrams of distribution of residual stresses in thickness (*b*) in welded specimen with longitudinal stiffeners welded-on on both sides: *1* — in initial state after welding; *2* — after UIT and holding in corrosion environment [36]

is connected with the hardening of welded joint only on one (outer) side of the pipe and redistribution of stresses as a result of cutting.

In the work [27] the results of tests of T-welded joints of low-alloyed steel 10KhSND (σ_y = 390 MPa) in air and in corrosive environment (3 % solution of NaCl) in the initial state after welding and after hardening applying UIT are given. It was established that the corrosive environment reduces the limit of endurance margin based on $2\cdot10^6$ cycles of stress changes of welded joints in the initial state by 15 % (from 124 to 10^5 MPa), and by 29 % (from 260 to 185 MPa in the hardened state applying UIT). It is shown that the application of HMP is expedient, since it increases the limit of the endurance margin of welded joints in 3 % solution of NaCl by 76 % (from 105 to 185 MPa) and increases the cyclic life by 3.5 times. It is noted that fracture of hardened specimens applying UIT in the corrosive environment occurs along the base metal far from fusion line.

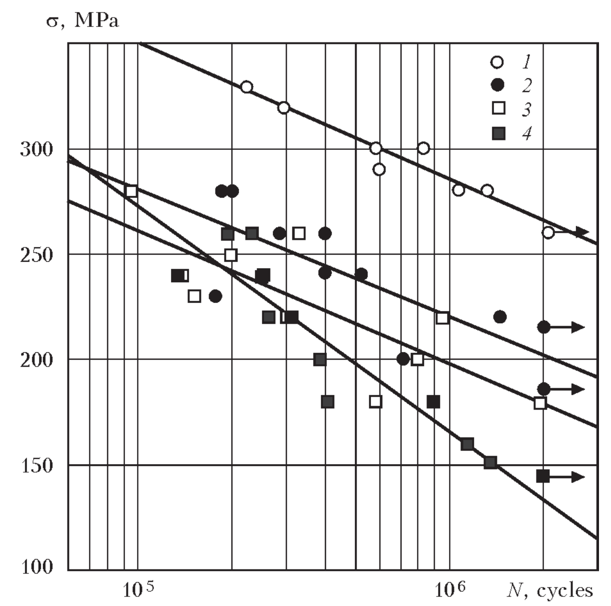

Figure 4. Fatigue curves welded T-joints of steel 15KhSND: *1*, *3* — in states hardened and unhardened by HMP in air, respectively; *2*, *4* — in states hardened and unhardened by HMP after effect of neutral salt fog during 1200 h, respectively [37]

All the literature data on efficiency of hardening welded joints by applying SPD (including UIT) methods considered above, which are susceptible to influence of corrosive environment, are associated with the experimental determination of corrosion fatigue characteristics of joints during their hardening in the as-welded state. It should be noted that during tests on corrosion fatigue in the solutions of NaCl, the time of staying welded specimens in the corrosive environment was from 10 to 200 hours. The works are being appeared devoted to long-term effect of aggressive environment on the state of plastically-deformed metal layer of welded joints hardened applying UIT, and, therefore, on the level of the induced residual compressive stresses and fatigue resistance characteristics [36, 37].

In the work [36], the residual stress fields of welded joints in the initial state, after hardening applying UIT and after hardening applying UIT followed by holding in the corrosive environment were investigated. The specimens of welded joints were manufactured of shipbuilding steel DH36 by its welding-in to the 25 mm thick plate on both sides of longitudinal stiffeners of 15 mm thickness. The holding of specimens in the corrosive environment (in synthetic sea water) was equivalent to 7.5 years of the structure service. The measurement of residual stresses in the surface layer of metal was carried out by X-ray and neutron non-destructive methods as well as by measuring the displacements after cutting the specimens by electroerosion method. It was established that application of UIT technology leads to inducing of residual compressive stresses in the near-surface layer of metal to the depth of more than 1 mm. It is shown that during holding in the corrosive environment, the corrosion-mechanical losses of surface layer of the specimen metal occurs. While comparing the weld metal to the base metal, the minimum losses (up to 1 mm) after holding in the corrosive environment along the hardened fusion line were recorded. It was established that despite the significant reduction in the maximum level of induced compressive stresses on the surface, due to the partial loss of the hardened metal layer, they were almost unchanged in depth (Figure 3).

In the work [37] the influence of long-term action of the corrosive environment on the efficiency of improvement of characteristics of the fatigue resistance of welded joints of steel 15KhSND applying UIT was investigated. It was shown that in holding of welded joints, hardened applying UIT technologies, in the chamber of neutral salt fog during 1200 hours leads to formation of complex corrosion damages in the plastically deformed layer of metal: caverns transforming into pittings and corrosion cracks passing into caverns. It was found that in spite of partial damage to the hardened metal layer, the cyclic life of the joints is increased by 2–5 times depending on the levels of applied stresses, and the limit of endurance margin on the base of $2\cdot10^6$ cycles of stress changes is increased by 48 % (Figure 4). The fracture of specimens, hardened applying UIT, occurs along the base metal far from the weld and HAZ.

It is important to note that in this research direction there are no works devoted to the problems of establishing the efficiency of application of SPD methods to the in-service metal structures, the welded elements of which have a certain level of corrosion-fatigue damages.

Conclusions

1. The experimental investigations of the recent years are devoted mainly to the establishment of efficiency of application of both conventional (shot blasting, pressure treatment, etc.) as well as rather new methods of surface plastic deformation of metal (pulsating high power electron beam, fusion of surface using nanopulsed laser) to increase the corrosion fatigue resistance and corrosion resistance of base metal and welded joints.

2. Almost all the SPD methods (except of grinding) increase the roughness of the treated surface and, consequently, the effective surface area, which facilitates the increase in the corrosion rate of the metal. To increase the corrosion resistance of the surface layer of metal hardened by SPD methods, resulting in increase of surface roughness, it is advisable to apply additional measures for passivation of the surface (deposition of a thin hydroxyapatite film, nitriding, grinding to a depth of 10–15 μm, holding in 20 % solution NHO_3, etc.).

3. The SPD methods contribute to an increase in the corrosion resistance of welded joints, which is initially lower than the base metal, following the change in the structure of the surface layer metal and the substantial relaxation of the residual tensile stresses (or inducing the residual compressive stresses). For the treatment of welded metal structures, ultrasonic impact treatment (UIT) is the most promising due to the compactness and mobility of the equipment, the good ecology of technological process, high efficiency, ability of hardening the welded joints in any spatial positions in the field conditions.

4. Hardening of welded joints of stainless steels applying UIT technology, in addition to grinding the structure of the metal to nanosizes, increasing hardness and wear resistance, leads to formation of oxide film with an increased chromium content on the surface. Hardening of stainless steels specimens should be performed after preliminary determination of optimal technological parameters, since the amount of martensite increases with the treatment time increase (correspondingly, the galvanic effect between austenite and martensite increases), which leads to a decrease in corrosion resistance.

5. The corrosive environment reduces the efficiency of hardening the welded joints applying SPD methods to improve the resistance to fatigue as compared with the air tests. However, the application of SPD methods is reasonable, since it allows a significant increase in the cyclic life and the limit of endurance margin of welded joints under the influence of corrosive environment as compared to the unhardened joints.

6. At the long-time effect of corrosive environments on welded joints, hardened by SPD methods, a partial corrosion-mechanical and mechanical losses of the plastic deformed surface layer of metal, the formation of defects in the form of caverns, pittings, etc., occur. This leads to a significant decrease in the maximum level of induced compressive stresses on the surface, but in depth they practically do not change. At the same time, the characteristics of the fatigue resistance of welded joints with the damaged hardened metal layer remain higher than in the initial state.

7. There are no works devoted to the problems of establishing the efficiency of application of SPD methods to the in-service metal structures, the welded elements of which have a certain level of fatigue and corrosion damages.

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