Lyudmila Nyrkova, Sergiy Prokopchuk, Svetlana Osadchuk, Anatoliy Rybakov, Larisa Goncharenko*

E.O. Paton Electric Welding Institute of the National academy of sciences of Ukraine, Kiev, Ukraine

Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
UDC:669.141.25:621.643.411:669.018.8
doi: 10.5937/zasmat2004328N

Zastita Materijala 61 (4)
328 - 338 (2020)

Stress corrosion resistance of welded joints of low-alloy pipe steel produced by high frequency welding

ABSTRACT

The paper presents the results of stress corrosion resistance studies of welded joints of low-alloy steel 17G1SU, obtained by high-frequency welding (HFW). The potentiometry method has established that the welded joint in the state after welding and after linear heat treatment is resistant to corrosion, because the potential difference between the weld and the base metal does not exceed (30-50) mV. According to the results of accelerated corrosion-mechanical tests in 3% NaCl under conditions of constant load under different stress, it was found that the rate of uniform corrosion of both types of welded joints is almost the same as the base metal. Slightly higher corrosion rate of the welded junction after linear heat treatment correlates with the electrochemical data. In general, the welded joint, made according to the factory technology, has resistance to corrosion and mechanical destruction in a solution of 3% NaCl at the level of the base metal, in the absence of weld defects.

In the range of protective polarization potentials normalized by the standard of Ukraine, the ratio of the cathodic protection current to the diffusion current limit for the base metal and for the weld metal practically does not differ. It can be expected that under the conditions of cathodic protection, the predominant local flooding of the weld metal or the parent metal is not expected.

***Keywords**: low-carbon pipe steel 17G1S-U, welded joint, linear heat treatment, corrosion rate, stress corrosion resistance, potentiometry, method of polarization curves.*

1. INTRODUCTION

Welded pipes as compared to seamless pipes are characterized by a low cost, dimensional stability and the ability of manufacturing pipes of different standard sizes. In the manufacture of gas and oil line pipes, corrosion resistant low-alloy steels are widely used, which are produced by controlled rolling and have a high level of strength and ductile properties. The problem of improving the quality and expanding the range of rolled products is predetermined by outperforming production growth rates and an increase in strength requirements [1,2]. The pipes welded applying the technology of high frequency welding (HFW) have more advantages due to a lower cost of manufacturing unlike the pipes welded applying arc welding. HFW pipes are successfully used for oil and gas transportation [3,4]. However, a relatively low toughness of the weld as compared to other pipes restricts their application in high pressure systems. In recent years, due to the use of a new technology an improvement in the quality of HFW pipes is observed [5–9].

Many practical investigations are devoted to studying the characteristics of fatigue fracture, which, according to the authors [10,11], is one of the basic requirements to the pipeline integrity. Hence, the fatigue of steel pipelines and welded joints is widely investigated [12–15]. In [16] it is mentioned about the formation of a weakened zone in the weld area of the X70 pipe produced by high frequency welding. But mechanical properties, including strength and striking energy, are usually higher than the values standardized by the API specification. The decrease in strength, toughness and fatigue resistance of the welded joint are predetermined by an increased grain size in the weld area. However, for the specimens without a surface treatment, the fatigue resistance S-N for

*Corresponding author: Lyudmila Nyrkova
E-mail: lnyrkova@gmail.com, nyrkova@paton.keiv.ua
Paper received: 25. 09. 2020.
Paper accepted: 13. 10. 2020.
Paper is available on the website: www.idk.org.rs/journal

the welded joint is even lower. This is mainly associated with defects and an increased grain size in the heat-affected-zone. Thus, to improve the quality of HFW pipes of X70 steel, first of all, the measures should be taken to improve the microstructure of the welded joint and to reduce generated defects by optimizing post-weld heat treatment and edge preparation before welding.

In [17], an attempt was made to analyze the cause of arising through damages of steel pipes. The microstructure of the welded joints was compared and their corrosion properties were investigated in 3.5% NaCl. The results showed that the failure of steel pipes is explained by a poor fusion of edges as a result of a relatively low heat input.

In Ukraine, the production of gas-oil line pipes using the method of high frequency welding was organized in 1965. After 2005, at the pipe works a set of measures was performed in order to provide a significant technological improvement in the HFW pipes production, which allowed expanding the range of pipes manufactured for main gas and oil pipelines in compliance with the modern quality standard requirements [18,19].

As a result of the pronounced structural, mechanical and electrochemical inhomogeneity, the welded joints are distinguished by a reduced resistance to corrosion and mechanical fracture and a limited technical life of the pipes. Despite a large scope of carried out investigations, the problems of improving the efficiency of welded oil pipelines, in particular those, manufactured of modern low-carbon low-alloy steels, were not completely solved.

One of the main causes limiting the service life of such pipelines is the corrosion of inner wall [20-22], and the most vulnerable area is the area of welded joint [23,24].

Currently, in the process of manufacturing pipes two methods of welding are used – electric arc welding (EAW) and high frequency welding (HFW). In [22], it is shown that thick-walled welded joints made by HFW have higher corrosion properties as compared to EAW joints, since they have a smaller width of the heat-affected-zone and a homogeneous structure in the typical areas of welded joints. It is also noted that unlike EAW pipes, welded joints of thick-walled HFW pipes have higher corrosion but lower mechanical properties, since they have a smaller width of the heat-affected-zone and a homogeneous structure in the typical areas of welded joints.

The results of studying the mechanism of crevice corrosion of the HFW pipe produced in seawater are given in [23]. The crevice corrosion was developed selectively over the weld. Applying the method of scanning electron microscopy, it was found that corrosion damages begin directly at MnS inclusions and are locally distributed as a result of forming a galvanic couple between a narrow weld (anode) and the base metal (cathode).

Also the data were presented [24], showing that the local heat treatment of the welding area at 930°C (additional treatment before a full heat treatment at 690°C) contributed to the increase in the resistance to the development of crevice corrosion. It was shown that corrosion in the crevice is related to the microstructure and chemical composition of the weld. During the contact with neutral salt-containing media, HFW pipes of carbon and low-alloy steels may undergo major corrosion damage in the welding zone.

A study of the effect of welding and heat treatment modes on the mechanical properties and corrosion resistance of welded joints of pipes showed [25], that high frequency welding with a subsequent high-temperature annealing provides the strength and corrosion properties of welds in the pipes of low-carbon low-alloy steels on the level of the base metal.

In [26] the tensile strength and impact toughness of both the base metal and the welded joint of the HFW X52 pipes were investigated. The results showed that both the base metal and the welded joint have an excellent balance between the strength and impact toughness. However, welded joints have a lower cyclic durability than the base metal due to the effect of surface defects, which should be taken into account to evaluate the intensity of the pipes.

Therefore, along with the mechanical properties and resistance to fatigue fracture, the corrosion resistance of welded pipelines is one of the main properties that provides serviceability of the pipeline as a whole. Since the results of investigations found in the literature relate mainly to the mechanical, structural and fatigue properties, the study of electrochemical properties and the effect of the stress state on the corrosion strength of such welded joints look quite relevant to us.

The aim of the work consisted in studying the stress corrosion resistance of welded joints produced by high frequency welding.

2. EXPERIMENTAL

The studies were carried on the specimens of the base metal of 17G1S-U steel and welded joints produced by high frequency currents in the state after linear thermal treatment (LHT) of the weld and immediately after welding without LHT.

The welding speed was 15-15.2 m/min. The chemical composition of steel is shown in Table 1. The mechanical properties of the base metal and welded joints with LHT are presented in Table 2.

Table 1. Chemical composition of 17G1S-U steel

Tabela 1. Hemijski sastav čelika 17G1S-U

Grade of steel specimen, random length	Mass fraction of elements, %									
	C	Mn	Si	S	P	Al	Ni	Ti	V	Nb
17G1S-U	0.12	1.23	0.49	0.016	0.013	0.01	0.03	0.005	0.03	0.021
GOST 5520 [27]	0.15-0.20	1.15-1.6	0.4-0.6	0.040	0.035	-	-	-	-	-

Table 2. Mechanical properties of base metal and welded joints of 530 × 10.0 mm pipes of 17G1S-U steel

Tabela 2. Mehanička svojstva osnovnog metala i zavarenih spojeva cevi 530×10,0 mm od čelika 17G1S-U

Specimen characteristics	Mechanical properties				
	σ_y, MPa	σ_t, MPa	δ_5, %	KCV^{-20}, J/cm^2	KCU^{-40}, J/sm^2
Base metal	400-430	560-580	29-33	138-289	155-308
Welded joint with LHT	-	550-580	-	72-284	97-245

The electrochemical investigations were carried out in the pressure cell with a 9 mm diameter of the working part, which was mounted on the base metal or on the weld area. Before the investigations, the specimens were grinded with a sandpaper of various granularity from P320 to P1000, washed with running and distilled water and wiped with ethyl alcohol.

The corrosion potential was measured during 60 min. After establishing a constant value of the corrosion potential, the polarization curves were measured in the potentiodynamic mode by scanning the potential at a rate of 0.5 mV/s according to the three-electrode scheme. The working electrodes consisted of the base metal and the weld, and the auxiliary one consisted of the platinum plate, the reference electrode was the chlorine silver electrode (ch.s.e.).

The investigation of the metal structure in the welded joints was performed by using the optical metallography according to the standard procedure.

The corrosion-mechanical investigations of the base metal and welded joints were carried out during 1000 hours in 3% NaCl solution. The size of the specimens was (115×10×3) mm. The area of the joint weld without LHT was about (1.9-2.1)% from the total area of the specimen with LHT – (4.7-5.1)%. The specimens were tested in the unstressed and stressed states at a constant load according to GOST 9.901-2 [28] (method 4) with a periodic measurement after 240, 480 and 1000 h. The specimens were loaded under a four-point bending scheme in the central zone according to GOST 9.901.2 (paragraph 3.4.1.4). The bending arrow was calculated by the formula:

$$y = \frac{\sigma(3H^2 - 4A^2)}{12Et} \quad (1)$$

Where σ is the value of the specified stresses, MPa;

E is the modulus of elasticity, N/m;

t is the thickness of the specimen, m;

H is the distance between outer supports, m;

A is the distance between outer and inner supports, m.

The load was chosen equal to 0.95σ_y (380 MPa), 240 MPa (which corresponded to the working pressure in the pipeline) and twice lower than the working pressure – 140 MPa.

The rate of continuous corrosion was determined applying the massometry method according to the standard procedure. After exposing the specimens in the solution, a type of corrosion damages was determined and the degree of corrosion damage of the surface was evaluated.

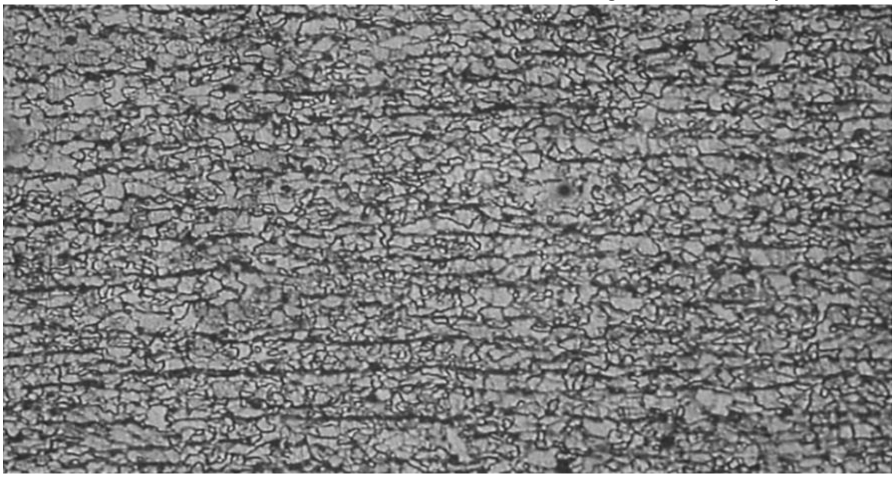
3. RESULTS AND DISCUSSION

3.1. Microstructure examinations

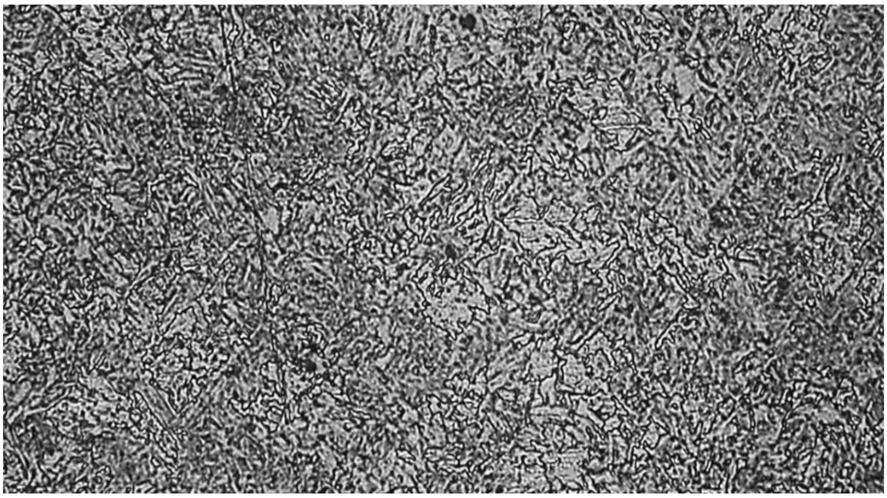
According to the results of metallographic examinations, it was found that the structure of the base metal of the pipes represented a mixture of fine-grained ferrite and perlite with a ferrite grain of 9-10 number (Fig.1*a*). The banding of the steel is characterized by the ball 4-5 according to the scale 3 GOST 5640 [29].

The contamination of the base metal occurs locally in separate zones – by slag inclusions, tiny globular oxides, elongated oxides, including those near the fusion zone (Fig. 1).

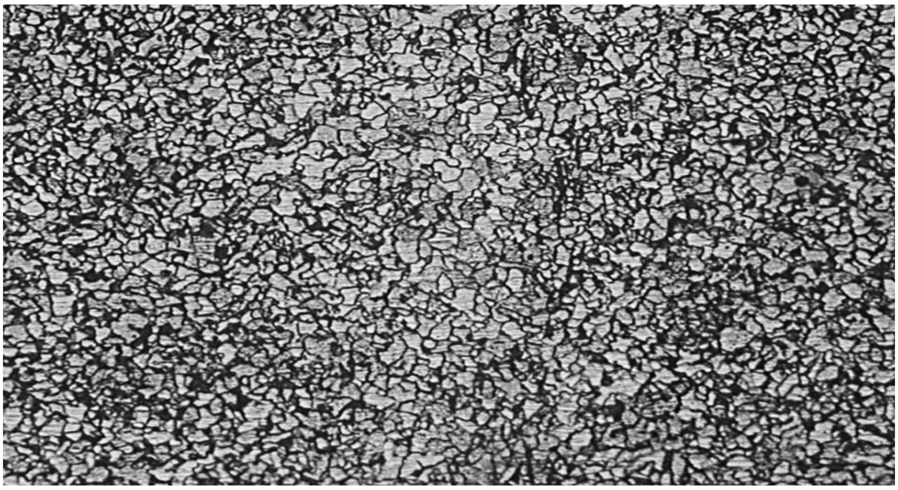
The structure of the welded joint without LHT is characterized by heterogeneity (Fig. 1*b*). Moreover, a significant delamination of the structure into separate zones is revealed: zone of fusion (a lighter layer with a low-carbon structure), zone of overheating and zone of partial recrystallization.



a)



b)



c)

Figure 1. Microstructure of different zones of HF welded joints of 17G1S-U steel: 1 – base metal; 2 – welded joints without LHT: 3 – welded joints after LHT

Slika 1. Mikrostruktura različitih zona HF zavarenih spojeva od čelika 17G1S-U: 1 - osnovni metal; 2 - zavareni spojevi bez LHT: 3 - zavareni spojevi nakon LHT

During a local heat treatment heating of welded joints occurred over the entire thickness of the pipes wall. The fusion line of welded joints in the form of a light decarburized band is almost perpendicular to the surface of the pipe, it may have a slight curvature. The zone of heat treatment in welded joints may be both symmetric and asymmetric. At the LHT zone, the metal microstructure represents a typical fine-grained ferrite-pearlite mixture (Fig.1c). The local heat treatment of welded joints certainly improves the metal structure of welded joints. The total width of the LHT zone on the outer surface of the pipe is (19-23) mm, and on the inner it is (10-13) mm. Based on the available experience, as the optimal zone of local heat treatment is considered, at which its width from the inner and outer side of the pipe is provided to be close as to its sizes.

3.2. Electrochemical investigations

The corrosion potentials of the specimens of the base metal and welded joints were determined. From the analysis of the experimental data it follows that the potential difference between the weld of the specimens without LHT and those with LHT and the base metal does not exceed (30-50) mV (Table 3 and Fig.2, 3). According to GOST 9.005 [30] (paragraph 4.4.5), such welded joints are corrosion resistant.

Applying the graphical-analytical method, from the polarization curves the following electro-chemical parameters were determined: current in the field of active anodic dissolution, anodic Tafel slope, limiting diffusion current, potential of hydrogen evolution beginning.

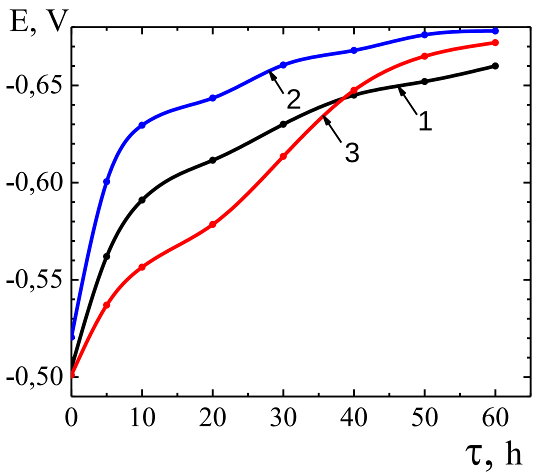


Figure 2. Change of corrosion potential with time, measured in different zones of welded joints: 1 – base metal, 2 – welded joint without LHT, 3 – welded joint after LHT.

Slika 2. Promena potencijala korozije sa vremenom, mereno u različitim zonama zavarenih spojeva: 1 - osnovni metal, 2 - zavareni spoj bez LHT, 3 - zavareni spoj nakon LHT

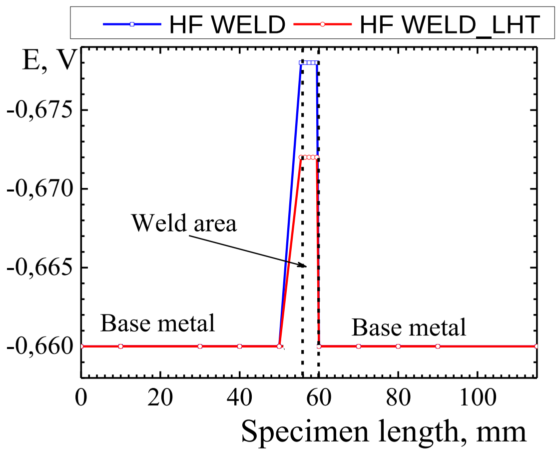


Figure 3. Change of corrosion potential along the length of welded joints

Slika 3. Promena potencijala korozije po dužini zavarenih spojeva

Table 3. Electrochemical characteristics of different zones of welded joints of 17G1S-U steel in the 3% NaCl solution

Tabela 3. Elektrohemijske karakteristike različitih zona zavarenih spojeva čelika 17G1S-U u 3% rastvoru NaCl

Zone of welded joint	E_k, V	**Electrochemical characteristics of processes**				**Currents of cathodic protection j_{CP}, A/m², at polarization potentials, V**		**Ratio j_{CP}/j_{O2}, at polarization potentials, V**	
		anode		**cathode**					
		b_a, V	*I*, A/m²	i_d, A/m²	E_{H2}, V	-0,75	-1,05	-0,75	-1,05
BM	-0.658	0.064	0.023	0.047	-0.79	0.048	1.03	0.04	0.92
W with LHT	-0.672	0.064	0.130	0.120	-0.87	0.093	0.65	0.07	0.5
W with LHT	-0.683	0.066	0.150	0.160	-0.94	0.144	0.70	0.1	0.5

Notes. E_k is the corrosion potential; b_a is the Tafel constant (slope of the anode polarization curve); *i* is the current density of the anode dissolution at a potential of -0.64 V; i_d is the density of the limiting diffusion current of oxygen reduction; E_{H2} is the potential for the beginning of hydrogen evolution.

The polarization curves are shown in Fig. 4. From their analysis it is seen that the character of the anode and cathode curves of both the base metal and the welds is the same. The value of the limiting current of oxygen reduction on the base metal is 2.5-3.4 times lower than in the area of the welds (0.047, 0.12 and 0.16 mA/m², respectively), Table 3. Since, under the conditions of a free access of oxygen in aqueous solutions, the corrosion proceeds with a diffusion control, higher currents of oxygen reduction in the welds area can contribute to accelerating the corrosion process in this area, which needs a greater attention. The potentials of the beginning of hydrogen evolution on the welds about (8-15) mV are more negative than on the base metal, Table 2.

Analyzing the behaviour of the anode curves, it is possible to note the area of active dissolution, from the corrosion potential to -0.5V (Fig.4, curves 1-3).

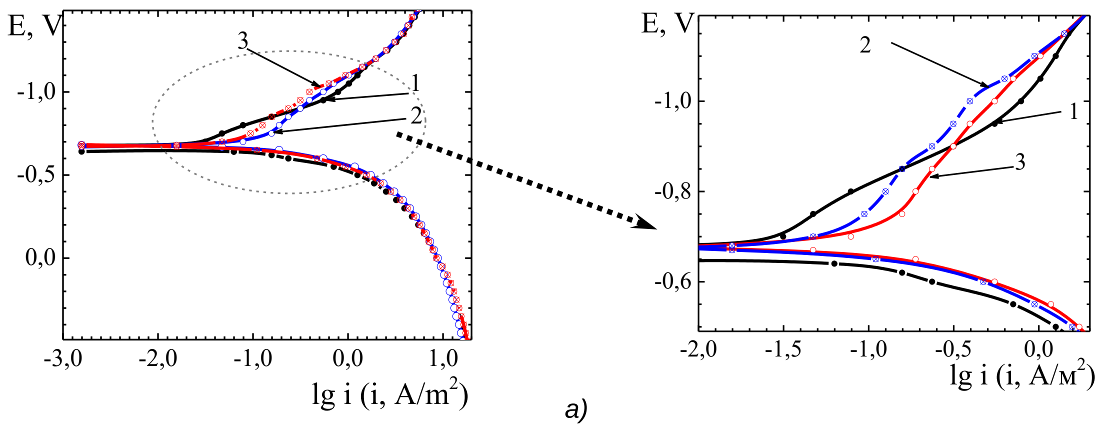


Figure 4. Polarisation curves of different zones of welded joints of 17G1S-U steel in the 3 % NaCl solution: 1 – base metal; 2 – welded joints without LHT: 3 – welded joints after LHT

Slika 4. Krive polarizacije različitih zona zavarenih spojeva čelika 17G1S-U u 3% rastvoru NaCl: 1 - osnovni metal; 2 - zavareni spojevi bez LHT: 3 - zavareni spojevi nakon LHT

The angle of inclination of the anode curves (anode inclination b_a) is about 0.06V, Table. 2, which indicates the diffusion control of the process of dissolution of both the base metal and the welds. At the same potential, for example, -0.64V, the rate of anodic dissolution of the base metal is 5.7-6.5 times lower than that of the weld without LHT and with LHT, respectively, Table. 3. At the potentials higher than -0.5V, a slow anodic dissolution was observed, predetermined by shielding the surface with the iron corrosion products.

3.3. Corrosion resistance under stress

During the contact with the solution, on the surface a layer of brown corrosion products of light and darker shades was formed, which is characteristic for iron oxides.

In a neutral solution with a neutral pH, the main cathode and anode reactions of the steel are the following:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (2)$$

$$Fe \rightarrow Fe^{2+} + 2e^- . \quad (3)$$

In the aqueous medium at a free access of oxygen, Fe^{2+} ions are oxidized to Fe^{3+}:

$$Fe^{2+} - e^- \rightarrow Fe^{3+} \quad (4)$$

Then, Fe^{2+} ions at the contact with the medium in the near-electrode layer form an iron hydroxide on the metal surface:

$$Fe^{3+} + 3OH^- \rightarrow Fe(OH)_3 . \quad (5)$$

Simultaneously, on the surface parallel reactions proceed, the ions of Fe^{2+} and Fe^{3+} hydrolyze with the formation of hydroxides $Fe(OH)_2$ and $Fe(OH)_3$. Hydroxide $Fe(OH)_3$ can also be represented as a formula $2Fe(OH)_3$ or $Fe_2O_3{\cdot}3H_2O$.

After removal of corrosion products on the surface, corrosion spots of different sizes were revealed, Figure 5). The spots are visually characterized by a change in colour of the surface layer (darkening) with a very small depth of damage. On the surface of some specimens, small corrosion ulcers with a diameter from 1 to 4 mm were formed. The localization of corrosion damages and a predominant corrosion fracture in the weld were not observed.

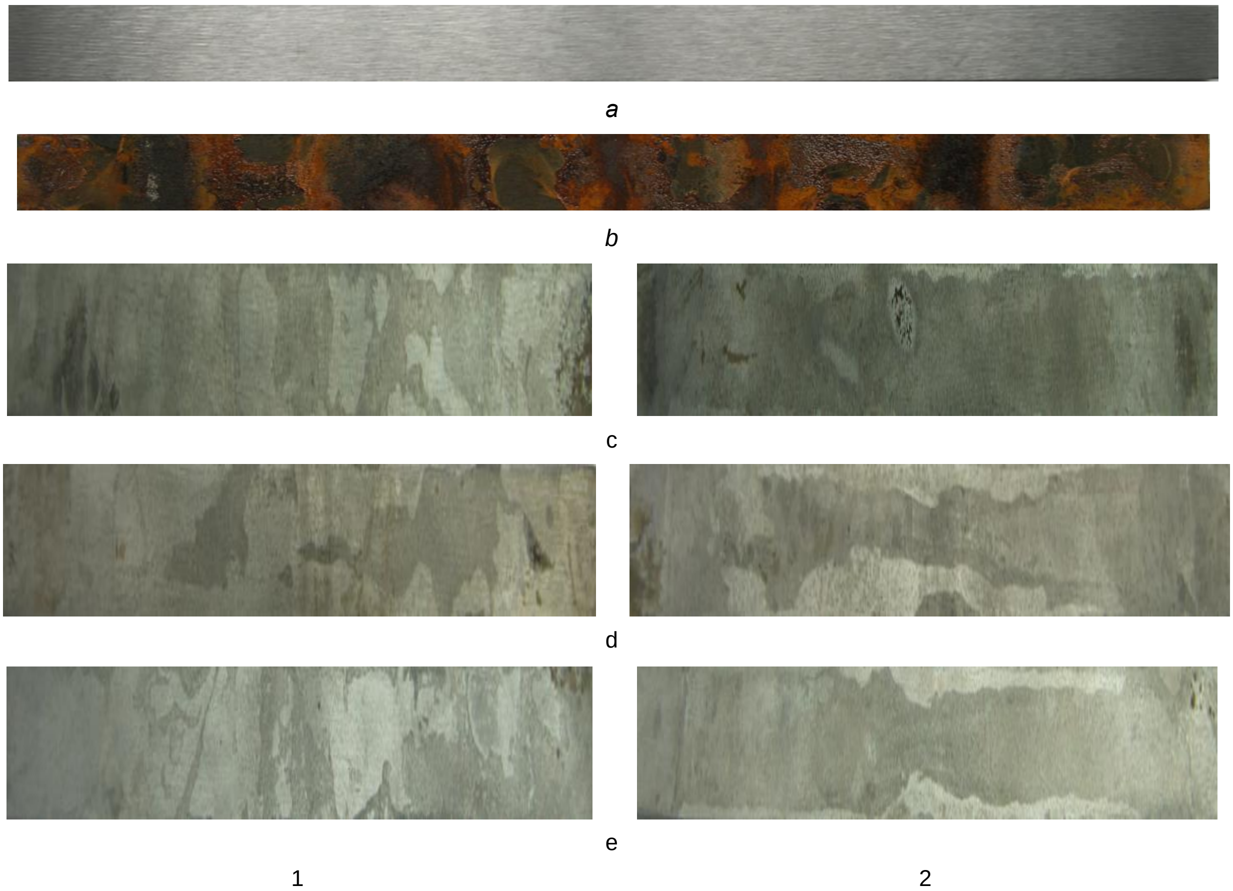


Figure 5. Appearance of the surface of specimens of 17G1S-U steel before (a) and after corrosion and corrosion-mechanical tests (b – e) during 1000 h in the 3% NaCl solution: 1 – in unstressed state; 2 – in stressed state; a – before the tests; b – after the tests without a removal of corrosion products; c – base metal; d – welded joint without LHT; e – welded joint after LHT

Slika 5. Izgled površine uzoraka čelika 17G1S-U pre (a) i posle korozije i korozijsko-mehaničkih ispitivanja (b - e) tokom 1000 h u 3% rastvoru NaCl: 1 –u nenapregnutom stanju; 2 - u napregnutom stanju; a - pre testova; b - nakon ispitivanja bez uklanjanja proizvoda korozije; c - osnovni metal;d - zavareni spoj bez LHT; e - zavareni spoj nakon LHT

The degree of damage of the specimen surface by corrosion spots was slightly different for the specimens in the unstressed and those in the stressed states: in general, the area of the unstressed specimens covered by corrosion spots ranged approximately from 40 to 50% and that of the stressed ones – from 70 to 90%, Fig. 6 a.

The rate of a continuous corrosion of welded joints of steel 17G1S-U without LHT and with LHT in the unstressed state for 500 hours is close to that of the base metal, however after 1000 hours, the acceleration of corrosion of welded joints with LHT to about 60% is observed, which correlates with the results of electrochemical tests. According to the corrosion-resistance scale for metals [19], the corrosion resistance of the base metal and the welded joint without LHT after 1000 hours was evaluated by the ball 5, and the metal was evaluated as "stable", and that of the welded joint with LHT was evaluated by the ball 6, which corresponded to the resistance group "reduced resistant" (Fig. 6, b).

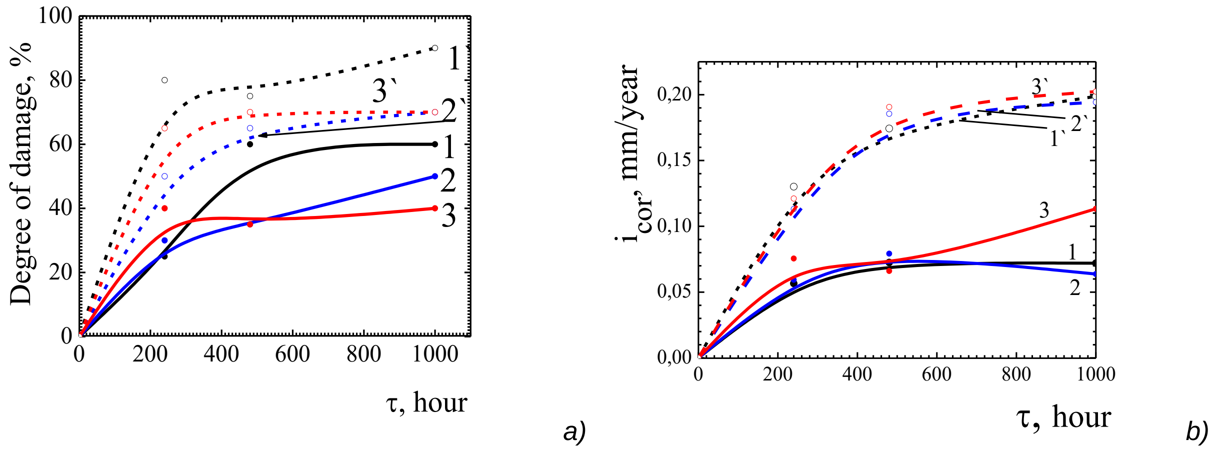


Figure 6. Degree of surface damage by corrosion (a) and corrosion resistance (b) of the base metal and welded joints of 17G1S-U steel after corrosion-mechanical tests in the 3% NaCl solution: 1, 1` is the base metal in the unstressed and stressed states; 2, 2' is the welded joint without LHT in the unstressed and stressed states; 3, 3' is the welded joint after LHT in the unstressed and stressed states

Slika 6. Stepen površinskog oštećenja korozijom (a) i otpornošću na koroziju (b) osnovnog metala i zavarenih spojeva od čelika 17G1S-U nakon korozijsko-mehaničkih ispitivanja u 3% rastvoru NaCl: 1, 1` je osnovni metal u nenapregnutom stanju i napregnutom stanju; 2, 2' je zavareni spoj bez LHT u nenapregnutom i napregnutom stanju; 3, 3 ' je zavareni spoj nakon LHT u nenapregnutom i napregnutom stanju

When the specimens are loaded to the level of 0.95 from the yield point of the base metal, the rate of continuous corrosion after 1000 h increases by 1.7-3 times, Fig. 6, b: from 0.072, 0.064 and 0.116 mm/year in the unstressed state (base metal, welded joint without LHT and welded joint with LHT, respectively) to 0.199, 0.194 and 0.202 mm/year in the stressed state, respectively. The corrosion resistance of all the specimens is evaluated by the ball 6, which corresponds to the "reduced resistant" metal.

For practical application, it is important to investigate the effect of the load level on the corrosion rate of the base metal and welded joints. Such investigations were performed during 1000 hours in a neutral solution. The following loads were selected: a load, to which a pipeline during its operation is subjected, a load twice lower than the operating one, and a load equal to 0.95 of the yield point. It was found that the rate of continuous corrosion of both types of welded joints (without LHT and with LHT) and that of the base metal is almost the same, Fig. 7.

A slightly higher value of the rate of corrosion of the welded joint with LHT at all the studied load levels correlates with the results of electrochemical data, Fig. 4. But in general, it should be noted that resistance of the welded joint, made in accordance with the factory technology, to corrosion-mechanical fracture in the 3% NaCl solution is at the level of the base metal. Despite a local decrease in the observed values of impact strength, the overall corrosion resistance of this welded joint is satisfactory in general. It should be noted that those data were obtained for the grinded state of the surface. During operation, as a result of the formation of probable surface irregularities in the weld area, the localization of the corrosion process is not excluded.

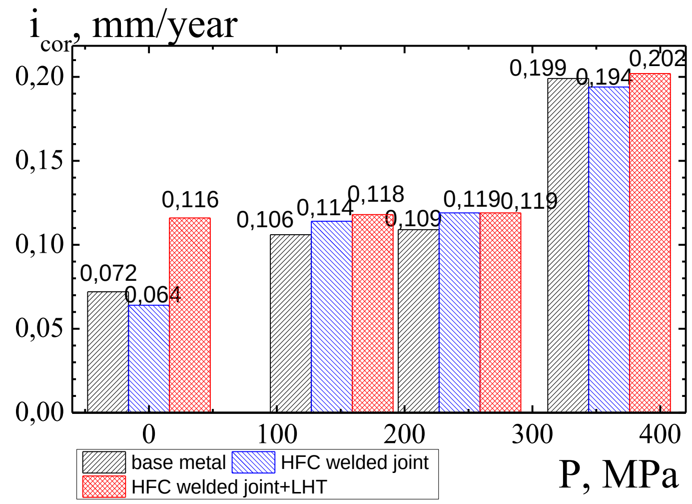


Figure 7. Effect of the load level on the resistance to corrosion of the base metal and welded joints of 17G1S-U steel

Slika 7. Uticaj nivoa opterećenja na otpornost na koroziju osnovnog metala i zavarenih spojeva od čelika 17G1S-U

3.4. Effect of cathodic protection potential on the corrosion state at area of tested weld

HFW-pipes are intended for the construction of main gas and oil pipelines, oil products pipelines, process and industrial pipelines [31]. Based on this, it was appropriate to investigate their behavior in the conditions under which the corrosion and stress-corrosion cracking may be initiated.

Analyzing the effect of the protective potential on the corrosion state of the pipe surface, some authors propose to determine the current density of the cathodic protection and to compare it with the density of the limiting current of oxygen reduction [32]. If the ratio of currents is lower than 1, the corrosion of the pipe wall in the coating defect is probable; if the ratio of currents is in the range from 1 to 3 – the protective effect is achieved, the further increase in the current density of the cathodic protection does not result in a significant reduction in the corrosion rate, but is accompanied by a sharp increase in the volume of hydrogen formed during the electrolyte decomposition. As far as the welded joints have some electrochemical heterogeneity, the analysis of the currents ratio $j_{K.3.}/j_{O2}$ was performed for the area of the weld and the base metal in order to establish the possible formation of local areas with different electrochemical activity on the surface of the pipe under the delaminated coating.

From the cathode polarization curves (Fig.4), the density of the limiting diffusion current and the current of cathodic protection were determined at different protective polarization potentials and their ratios $j_{K.3.}/j_{O2}$ were analyzed, Table 3.

From the analysis of the experimental data it follows that in the range of protective potentials (from -0.85 V to -1.15 V relative to the copper sulfate electrode, which corresponds to the range from -0.75 V to -1.05 V relative to the chlorine-silver electrode) which is specified by DSTU 4219 [33], the currents ratio $j_{K.3.}/j_{O2}$ in the solutions of different aggressiveness on both the base metal and the weld metal is more than 1 according to the polarization potential approaching the maximum protective one. Such conditions contribute to the electrolyte decomposition with the hydrogen evolution. However, it should be noted that the currents ratio $j_{K.3.}/j_{O2}$ for the base metal and for the weld metal has almost no difference. This indicates that during operation under the conditions of the cathodic protection a predominant hydrogenizaiton of the weld metal or the base metal is not expected.

4. CONCLUSION

1. Applying the potentiometric method, it was found that in the post-weld state and after linear heat treatment the welded joint is corrosion-resistant, since the difference of potentials between the weld and the base metal does not exceed (30-50) mV. The corrosion mechanism of both the base metal and the welds is controlled by the oxygen diffusion, which is confirmed by the values of the anodic slopes b_a (about 0.06 V).

2. Based on the results of accelerated corrosion-mechanical tests in the 3% NaCl solution under the conditions of a permanent load under the operational load and the load, which is significantly higher than the operational one (0.95 from the yield point), it was found that the rate of continuous corrosion of the both types of welded joints (in the state after welding and after linear heat treatment)

and the base metal is almost the same. At all the investigated loading levels, a slightly higher value of the corrosion rate of the welded joint after linear heat treatment correlates with the results of the electrochemical data. In general, in the 3% NaCl solution a welded joint, made according to the factory technology, have a resistance to corrosion-mechanical fracture at the level of the base metal if defects in the weld are absent.

3. In the range of protective polarization potentials, the ratios of the cathodic protection current to the limiting diffusion current j_{CP}/j_{O2} for the base metal and for the weld metal, specified by the standard of Ukraine, are almost the same. It can be expected that under the conditions of cathodic protection, the preferred local hydrogenization of the weld metal or the base metal is not expected.

Acknowledgements

The work was carried out within the framework of the departmental order program of the National Academy of Sciences of Ukraine by the E.O. Paton Electric Welding Institute in 2019-2020 (fundamental research works) "Improving the operational reliability of main pipelines and oil storage tanks by providing technological guarantees for the quality of welded joints and optimizing the conditions of their safe operation" (State registration number 0118U100537).

5. REFERENCES

[1] V.Salganik, M.Rumyantsev (2007) Steel sheets production technology, Educational manual, publisher MSTU, p.320.

[2] M.Chukin (2015) Development of the theory of metal products quality, Quality in materials processing, 1, 5-10.

[3] T.Okabe, K.Yasuda, K.Nakata (2016) Dynamic observations of welding phenomena and finite element analysis in high- frequency electric resistance welding, Welding International, 11, 835–845.

[4] G.Khalaj, H.Pouraliakbar, M.Jandaghi, R.Gholami (2017) Microalloyed steel welds by HF-ERW technique: novel PWHT cycles, microstructure evolution and mechanical properties enhancement, International Journal of Pressure Vessels and Piping, 152, 15–26.

[5] D.Kim, T.Kim, Y.Park, K.Sung, M.Kang, C.Kim (2007) Estimation of weld quality in high-frequency electric re- sistance welding with image processing, Welding Journal, 86, 71–79.

[6] T.Fukami, N.Mizuhashi, N.Hasegawa, H.Hamatani, Y.Hasegawa, T.Asano, S.Motoyoshi, T.Miura, K.Tanaka, T.Nakaji, K.Yamamoto (2012) Development of the new welding control method for HF-ERW pipes– advanced welding process of HF-ERW 1. Proceedings of the Biennial International Pipeline Conference, 3, 229–236.

[7] H.Hamatani, N.Mizuhashi, T.Fukami, Y.Karube, T.Miura, K.Tanaka, T.Nakaji, K.Yamamoto, Y.Hasegawa (2012) Development of a new optical monitoring system of welding conditions for producing HF-ERW line pipes with high weld seam toughness–advanced welding process of HF-ERW 2. Proceedings of the Biennial International Pipeline Conference, 3, 237–245.

[8] H.Hamatani, F.Watanabe, N.Mizuhashi, S. Takeuchi, Y.Hirota, S.Matsubayashi, K.Tsukakoshi, Y.Hasegawa, T.Asano, T.Motoyoshi, T.Miura, K. Tanaka, K.Yamamoto, T.Nose, O.Solonenko, A.Smirnov (2012) Development of laminar plasma shielded HF-ERW process–advanced welding process of HF-ERW 3. Proceedings of the Biennial International Pipeline Conference, 3, 211–218.

[9] P.Simion, V.Dia, B.Istrate, C.Munteanu (2014) Controlling and monitoring of welding parameters for micro-alloyed steel pipes produced by high frequency electric welding, Advanced Materials Research, 1036, 464–469.

[10] B.Pinheiro, I.Pasqualino, S.Cunha (2014) Fatigue life assessment of damaged pipelines under cyclic internal pressure: pipelines with longitudinal and transverse plain dents, International Journal of Fatigue, 68, 38–47.

[11] J.Zhao, X.Chen, K.Chevil (2017) Efect of pressure sampling methods on pipeline integrity analysis. Journal of Pipeline Systems Engineering and Practice, 4, article 04017016.

[12] M.Neves Beltrão, E.Castrodeza, F.Bastian (2011) Fatigue crack propagation in API 5L X-70 pipeline steel longitudinal welded joints under constant and variable amplitudes, Fatigue and Fracture of Engineering Materials and Structures, 5,321–328.

[13] O.Fatoba, RAkid (2014) Low cycle fatigue behaviour of API 5L X65 pipeline steel at room temperature, Procedia Engineering, 74, 279–286.

[14] J.R. Pereira, A. Jesus, A.Fernandes, G.Varelis (2016) Monotonic, low-cycle fatigue, and ultralow-cycle fatigue behaviors of the X52, X60, and X65 piping steel grades, Journal of Pressure Vessel Technology, 3, article 031403.

[15] C.Taylor, S.Das, L.Collins, M.Rashid (2017) Fatigue crack growth at electrical resistance welding seam of API 5L X-70 steel line pipe at varied orientations, Journal of Offshore Mechanics and Arctic Engineering, 3, article 031401.

[16] P.Tian, K.Xu, G.Lu, G.Qiao, F.Xiao (2018) Low-Cycle Fatigue Properties of the X70 High-Frequency Electric-Resistant Welded Pipes, Advances in Materials Science and Engineering, 2, 1-10.

[17] B.Lee, S.Lee (2004) Studies on the microstructure and corrosion characteristics of electrical resistance welded steel, Key Engineering Materials, 270, 2327-2331.

[18] Yu.Antipov, E.Dmitrenko, A.Kovalenko, S. Goryanoy, A.Rybakov, S.Semenov, T.Filipchuk (2009) Improving the operational reliability of gas and oil line pipes manufactured by the method of high frequency welding, Strength problems, 5, 147-153.

[19] Yu.Antipov, E.Dmitrenko, A.Kovalenko, S. Goryanoy, A.Rybakov, S.Semenov, T.Filipchuk (2014) Technology of manufacturing gas and oil line pipes by the method of high frequency welding at the JSC «Interpipe NMPP» Avtomaticheskaya Svarka, 3, 43-49.

[20] L.Vyboyschik, R.Luchkin, A.Ioffe (2010) Providing corrosion resistance of welded joints of oil pipelines at the level of weld metal, Vektor Nauki TGU, 4, 60-64.

[21] L.Vyboyschik, N.Sopin, M.Kolosovsky, E.Ermolchik, A.Abuzdin (2020) Quality evaluation of welded joints according to the standards of structure. https://vosafety.ru/publikatsii/otsenka-kachestva-svarnyh-soedinenij-po-etalonam-struktury. Accessed August 21, 2020.

[22] R.Luchkin, L.Vyboyschik (2006) Improving homogeneity of structure and properties of welded joint of oil line pipes. Proceedings of the All-Russian Scientific and Technical Conference with International Participation «Modern Problems of Improving the Efficiency of Welding Production», p.134-140.

[23] C.Kato, Y.Otoguro, S.Kado, Y.Hisamatsu (1978) Grooving corrosion in electric resistance welded steel pipe in sea water, Cor. Sci.,1, 61-74.

[24] Z.Wang, X.Jing (2012) Grooving corrosion of oil coiled tubes manufactured by electrical resistance welding, Cor. Sci., 57, 67-73.

[25] L.Vyboishchik (2013) Formation of structure and properties in welded joints of oil line pipes, Metal science and heat treatment, 9-10, 535-539.

[26] P.Tian, K.Xu, G.Lu, G.Qiao, BLiao (2018) Evaluation of the mechanical properties of the X52 high frequency electric resistance welding pipes, Int. Journal of Pressure Vessels and Piping, 165, 59-67.

[27] Sheet products of carbon, low alloy and alloy steel for boilers and vessels working under pressure. Technical specifications. GOST 5520−79.

[28] Unified system of corrosion and ageing protection. Metals and alloys. Tests for corrosion cracking of specimens in the form of bent beam. GOST 9.901-2-89.

[29] Steel. Metallographic method for determination of microstructure of sheets and bands. GOST 5640-68.

[30] Unified system of corrosion and ageing protection. Metals, alloys, metallic and non-metallic coatings. Permissible and impermissible contacts with metals and non-metals. GOST 9.005-72.

[31] Unified system of corrosion and ageing protection. Inhibitors of metals corrosion for aqueous systems. Methods of corrosion tests. GOST 9.502-82.

[32] Pipe steels for gas and oil main pipelines. Technical specifications. GOST 202951-85

[33] V.Khizhnyakov, Yu.Kudashkin, M.Khizhnyakov, A.Zhilin (2011) Corrosion cracking of stress-strain pipelines during oil and gas transportation. Bulletin of the Tomsk Polytechnic University, Chemistry, 3, 84-89.

IZVOD

OTPORNOST PREMA NAPONSKOJ KOROZIJI ZAVARENIH CEVI OD NISKOLEGIRANOG ČELIKA PRIMENOM VISOKOFREKVENTNOG INDUKCIONOG ZAVARIVANJA

Predstavljeni su rezultati izučavanja otpornosti prema naponskoj koroziji zavarenih spojeva od niskolegiranog čelika 17G1SU, ostvarenih primenom visokofrekventnog zavarivanja (HFW). Potenciometrijska metoda je pokazala da je zavareni spoj, u stanju po zavarivanju i nakon neprekidnog žarenja (LHT), otporan na koroziju, što je protumačeno postojanjem potencijalne razlike između vara i osnovnog materijala koja nije prelazila 30-50mV. Prema rezultatima ubrzanog koroziono-mehaničkog ispitivanja u 3%NaCl pod dejstvom istog opterećenja a pri različitim naponima, nađeno je da je brzina uniformne korozije zavarenog spoja uglavnom ista kao u osnovnom materijalu. Nešto viša brzina korozije u zavarenom spoju a nakon neprekidnog žarenja je u korelaciji sa elektrohemijskim podacima. Uopšte, zavareni spoj urađen po fabričkoj tehnologiji i bez zavarivačkih grešaka, pokazao je otpornost prema koroziji i mehaničkom razaranju u 3% rastvoru NaCl na nivou osnovnog metala. U opsegu zaštitnog polarizacionog potencijala, propisanog od strane Ukrajinskog standarda, odnos katodne zaštitne struje prema graničnoj vrednosti struji difuzije, praktično se ne razlikuju između osnovnog metala i metala vara. Pod uslovima katodne zaštite, neko značajnije lokalno strujanje između metala vara i osnovnog metala se ne očekuje.

Ključne reči: *niskougljenični čelik za cevi 17G1SU, zavareni spoj, neprekidno žarenje, brzina korozije, otpornost prema naponskoj koroziji, potenciometrija. metoda polarizacionih krivih.*

Naučni rad

Rad primljen: 25. 09. 2020.

Rad prihvaćen: 13. 10. 2020.

Rad je dostupan na sajtu: www.idk.org.rs/casopis