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Analysis of corrosion fatigue steel strength of pump rods for oil wells

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Abstract

Purpose. is to perform analysis of corrosion durability (fatigue) of pump rod materials in terms of various chemically active simulation environments, and study influence of economically modified rare-earth impurity on corrosion fatigue strength of pump rod materials.

Methods. 40 and 20N2M steel grades have been applied as well as experimental steel (ES). Steel of the conditinal ES grade has been melted within a pilot site of Institute of Electric Welding Named after E.O. Paton of the National Academy of Sciences of Ukraine. The steel was alloyed economically by means of a micro impurity of a rare-earth element (REE) being 0.03% of cerium; in addition, it contained comparatively low concentration of sulfur and phosphorus as well as minor concentration of dissolved hydrogen. The following has been used as simulation environments: 1) NACE environment (i.e. 5% NaCl solution which contained 0.5% CH_3COOH, and saturated H_2S; $t = 22 \pm 2$°C; pH = 3.8-4.0); 2) 3% NaCl solution without hydrogen sulphide. Once every day, the environment was replaced to oxygenate it up to 8-10 mg/l concentration.

Findings. Stability against sulfide stress-corrosion cracking (SSCC), hydrogen initiated cracking (HIC), and corrosion fatigue of steel of deep pump rods for oil industry has been studied. It has been defined that the experimental steel, modified economically by means of micro impurities of a REE, meets NACE MR0175-96 standard in terms of chemical composition as well as strength; in turn, 20N2M and 40 steel grades have high resistance neither to SSCC (threshold stresses are < 0.8 s) nor to corrosion fatigue attack; moreover, steel grade 40 has demonstrated low resistance to HIC (CLR > 6% and CTR > 3%).

Originality. It has been identified that corrosion fatigue attack results from hydrogen penetration of steel initiating its cracking and hence destruction under the effect of alternating loads accelerated by the action of corrosive environment. Further, surface micro destructions, influenced by micro stresses, transform into large discontinuities and cracks with following macro destructions.

Practical implications. It has been proved that high resistance to corrosion cracking can be achieved by means of refining of pump-rod steel of ferrite and perlite type using metallurgical methods, i.e. 0.01-0.03% REE microalloying.

Keywords: *corrosion, steel, destruction, degradation, well, pump rods*

1. Introduction

It is known that a pump rod performance is among the most important factors determining overhaul operational period of oil [1]-[3]. From 2019 to 2020, Nafrogaz of Ukraine NJSC made 127 repairs due to rod breakages. On the ave-rage, it is 15% of the total repairs of downhole equipment. One of the most complex problems of repairless operation of underground facilities depends upon such factors as high bottomhole temperature; discharge of mechanical impurities from a seam; interval of permafrost rocks; aggressive components (i.e. sulfur, CO_2, combination of acid and alkaline solutions etc.) in the fluid; and paraffin deposits as well as hydrate formations. The abovementioned complicates significantly equipment performance and durability while increasing considerably prime cost of the produced oil. As the practices shows, 70-80% of rod breakages fall on 0-250 mm distance from a shoulder of rod groove within a so-called heat-affected zone (HAZ) [4], [5]. According to the available rod manufacturing technique, ends of pump rod workpieces should be heated up to 1150-1200°C. On the average, rod temperature is 20-22°C. Such a temperature gradient factors into varying graininess of structural components in HAZ as well as into 20% decrease in plastic characteristics and impact strength [6] causing micro stress gradient origination in the HAZ.

A problem of durable strength (fatigue) is intensified by GHM corrosion within the oil fields depending upon following conditions:

1) the GHMs, applied for oil wells, are of poor corrosion resistance while contacting directly with chemically aggressive working environment which is especially understood during long-term operation (i.e. for 15-20 years);

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2) the produced oil-water-gas mixture contains aggressive components, namely CO_2, chloride ions, sulfur acid ions, hydrogen sulfide etc. activating corrosion [7].

Moreover, reservoir water is highly mineralized brine; hence, corrosion processes in wells are of electrochemical nature. As a laboratory analysis has shown, general mineralization of reservoir water is 100-130 g/l. In this context, concentration of chloride ions achieves 98-100 g/l; specific weight of reservoir water is 1.09-1.12 g/cm^3; and concentration of hydrogen ions is 4.3-6.4 mg/l. It should be mentioned that corrosion activity of reservoir water depends upon a significant content of chloride ions and iron (40-50 mg/l) as well as availability of such corrosive ingredients as oxygen (1.23-1.54 mg/l), hydrogen sulfide (1.5-1.8 mg/l), and carbon dioxide (24.5-35.2 mg/l).

It is known [8] that any thermal and hydraulic impact disturbs natural cementing connections in a reservoir; consequently, well products contain excessive amount of mechanical impurities which range in oil wells is 60-150 mg/l [9]. In such cases, GHMs cannot operate correctly within the sites.

Hydraulic and abrasive flow effect on the surface of rod metal within the corrosive environment results in the destruction of hydro oxidative protective films. Destructive capacity of a flow depends upon the content of reservoir water, the weighed mechanical impurities, and the flow velocity in a well. Analysis of mechanical impurities of oil wells have shown that the impurities mainly contain quartz sand (60-70%) characterized by the greatest hardness among the basic rocks of productive oil seams [9]. Hydrogen phase and significant amount of mechanical impurities with the prevailing sand fraction support the idea of the intensified corrosion processes [10]. Earlier studies show that the majority of oil wells in Poltava Region have greater or lesser hydraulic and abrasive wear of pump rods. Corrosive and mechanical damage of the components of underground drilling equipment (i.e. casing pipes, tubing strings, and deep pump rods) mostly manifesting itself in the process of long-term operation in the aggressive environment in the context of simultaneous action of alternative steel loads has become the priority problem for oil industry.

Findings of domestic scientists and researchers [11] help conclude that oil wells demonstrate corrosion and erosion wear being one of the reasons reducing both performance and durability of well equipment and GHMs among other things. The wear is metal destruction, i.e. physical and chemical as well as mechanical action of corrosive environment resulting from the two simultaneous processes: electrochemical corrosion and mechanical destruction. Analysis of well stoppages makes it possible to mention that in the wells where carbon-acidic corrosion, and hydraulic and abrasive equipment wear are not available, even in the context of considerable content of mechanical impurities their shutdowns and complete wear are impossible both in the inhibited and uninhibited wells. Overhaul period in the wells where hydraulic and abrasive wear takes place but no carbon-acidic corrosion cannot be observed (even if corrosion inhibitors are not applied) is quite longer to compare with the wells in which inhibitor protection is used but hydraulic and abrasive wear is combined with carbon-acidic oxidization. Rather often, stoppage reason for such wells is GHM breakage.

Hence, overhaul well performance depends ambiguously upon the listed factors. If hydraulic and abrasive wear takes place, inhibitor protection cannot be always considered as an effective measure.

Increase in GHM performance period needs use of wear-and corrosion protective coats. Rods should be manufactured using corrosion-resistant materials. Hence, extra studies are required to look into reasons, mechanisms, and conditions under which rod metal degrades to improve performance durability.

Reliability augmentation of well facilities is possible if corrosive protective pipes and tubes are applied which will be alloyed economically by means of coagulation modifiers. In turn, they will experience complex thermal treatment. At the same time, they will have high corrosion fatigue characteristics during long-term operation period.

The abovementioned helps assume that operation of oil wells, equipped with rod deep pump facilities, may be restricted by strength and durability of pump rods. It is especially seen in the process of operation of wells characterized by high corrosion aggressiveness. Thus, search for methods improving long-term strength of pump rods, contacting corrosive environment, is the topical problem for the oil sector.

2. Methods of the research

40 and 20N2M steel grades as well as experimental steel (ES) were the study object. Steel of the conditional ES grade has been melted within a pilot site of Institute of Electric Welding Named after E.O. Paton of the National Academy of Sciences of Ukraine. The steel was alloyed economically by means of a micro impurity of a rare-earth element (REE) being 0.03% of cerium. In addition, it contained comparatively low concentration of sulfur and phosphorus as well as minor concentration of dissolved hydrogen (Table 1).

Table 1. Characteristics, chemical composition, and mechanical properties of pump rod metal

Steel grade	Thermal treatment	Alloying elements, %						$\sigma_в$, MPa	σ_m, MPa	H, %
		C	Si	Mn	S	P	others			
40	Annealing + tempering	0.38	0.22	0.85	0.022	0.024	–	520	410	0.0052
20N2M	Annealing + tempering	0.26	0.29	0.92	0.021	0.022	1.95Ni 0.46Mo	545	420	0.0039
ES	Hardening + high tempering	0.30	0.20	1.0	0.009	0.012	0.025Ce	≥ 550	≥ 450	0.0012

The following has been used as simulation environments: 1) NACE environment (i.e. 5% NaCl solution which contained 0.5% CH3COOH, and saturated H_2S; t=22±2ºC; pH=3.8-4.0); 2) 3% NaCl solution without hydrogen sulphide. Once every day, the environment was replaced to oxygenate it up to 8-10 mg/l concentration.

Corrosion velocity was defined using gravimetric technique with 480 h test period.

The samples, cut directly from the rods, were also tested as for their tendency to hydrogen initiated cracking (HIC) according to the International NACE TM-02-90 Standard since the test is obligatory while selecting material to manufacture oil facilities contacting hydrogen sulfide containing products [12]. HIC of rectangular samples with 100 mm length (along rolling), 16 mm width (across rolling), and *T* thickness (depending upon a rod diameter involving allowance for mechanical processing up to metallic luster) was analyzed. The test involves 96 h aging of the stressed samples in the synthetic NACE solution (5% NaCl solution +0.5% CH_3COOH; continuous H_2S saturation with 10 ml/min barbotage velocity; and pH = 3). Besides, minimum solution volume was 4 ml per 1 cm^2 of a sample surface [13]. Then, the samples were cut; the cut surface was polished and etched in the environment of chemical reagents. All the cracks, showed by ×100 zoom, were measured exclusive of those which distance from internal and external sample surfaces was up to 1 mm.

The measurement results have helped calculate coefficients of the steel sensitivity to hydrogen initiated cracking using following formulas: crack formation length coefficient $CLR = (\Sigma a / W) \cdot 100,\%$; and crack formation width coefficient $CTR = (\Sigma b / T) \cdot 100,\%$, where Σa and Σb – the total of longitudinal and transverse dimensions of crack formation areas, mm.

According to the International Specification, following requirements are imposed on hydrogen resistance of pipe steel: coefficients of crack length for HIC are $CLR \leq 6\%$; and crack thickness coefficients for HIC are $CTR \leq 3\%$. Table 2 explains plan of the experiment.

Table 2. Plan of the experiment

Material	Modifiers	Simulation environment	
		I	II
20N2M	–	X(1)	X(2)
40	–	X(3)	X(4)
ES	X	X(5)	X(6)

Tendency of rod steel to sulfide stress-corrosion cracking (SSCC) has been determined in accordance with NACE TM 01-77(90) Standard A method using cylindrical samples with 6.4 mm diameter permitted by thickness of the rod cross section [14]. The samples were tested under load using a weight type УСМР-6 device (each experiment applied five samples). In this context, threshold stress σ_{SSC} was identified to compare quality of different steel grades as well as diffe-rent manufacturers. In terms of the Standard, testing conditions are as follows: 720 hours in 5% NaCl solution containing 0.5% CH_3COOH, and H_2S saturated; pH = 3; and $t = 22 \pm 2$ºC.

σ_{SSC} parameter was determined from σ_i – log τ dependence (σ_i being initial loading; and τ being time to destruction, hours), in terms of which samples cannot be destroyed on the accepted time basis of the tests.

It should be mentioned that $\sigma_{tssc} / \sigma^{min}_{0.2}$ ratio is not standardized; nevertheless the ratio is that common criterion of steel serviceability in the hydrogen sulfide containing environment. If its value excesses 0.8 then the material is considered as a serviceable one [15].

σ_i – log τ dependence was developed depending upon the minimum time values up to destruction under each load since average τ rates are intolerable from the viewpoint of the supported oil equipment capacity in the technological environment with hydrogen sulfide.

Moreover, samples with 5 mm diameter were tested using a device of Instron type (the Great Britain). After the tests, the broken samples were randomly analyzed metalogrpahically with the help of electronic microscope YSM-35CF (JEOL Company, Japan). A composition of non-metallic inclusions was studied by means of energy dispersive microscope Link (the Great Britain). Television microscope Quantimet by Metal Research Company (the Great Britain) has helped identify volume share and geometry of the non-metallic inclusions.

3. Results and discussion

Figure 1 demonstrates results of metal corrosion velocity within the simulation NACE environments and 3% NaCl solution. Numbers of samples and steel grades correspond to those one shown in Table 2. It is understood that experimental ES steel proves the highest corrosion stability within the environments; in turn, samples of 20N2M and 40 steel grades are of low anticorrosion stability.

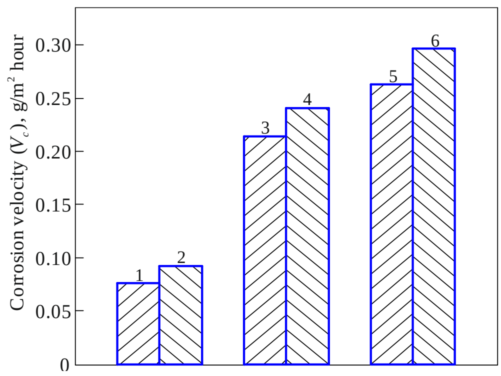

Figure 1. Diagram of corrosion velocities of GHMs rod samples with long-term (10 years) operation within such simulation environments as NaCl (1-3-5) and NACE (2-4-6)

3.1. SSCC analysis

Figure 2 explains a tendency of pump rod steel. Their signs correspond to numbers in Table 2.

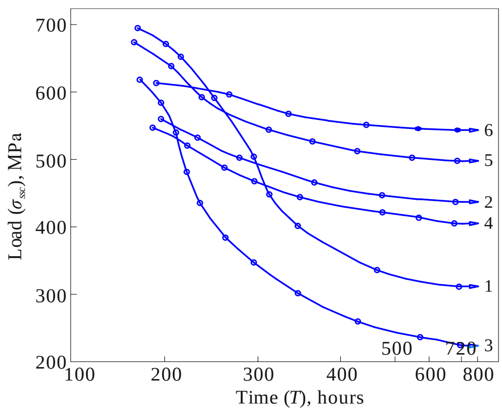

Figure 2. Tendency of deep pump rods to sulfide corrosion while testing in the simulation environments

It is seen that steel with conditional ES grade demonstrates the most intensive resistance to SSCC. 40 and 20N2M steel grades shown poor resistance to the specific corrosion. Nevertheless, it should be mentioned that the absolute σ_{tssc} values cannot be applied while designing oil well facilities due to nonavailability of reliable methods to define and forecast their fatigue (long-term) strength. The matter is that they may vary under the effect of numerous factors (i.e. concentration of hydrogen sulfide and carbon gas as well as their partial pressures; pH of environment; temperature of the pumped product; technological interruptions; equipment conditions etc.) [16]. Hence, strength calculation of deep pump rod strings of oil wells and their diameter determination with the help of output parameter should involve minimum allowable value of steel flow stress $\sigma^{min}_{0.2}$; in addition, suitability of structural materials is assessed with the help of threshold stresses expressed by an environment impact factor [17]: $k_{tssc} = \sigma_{tssc} / \sigma^{min}_{0.2}$.

It is commonly believed that steel can operate in the technological environments with highly corrosive components inclusive of hydrogen sulfide (up to 20 moles %) when $k_{tssc} \geq 0.8$ [17], [18].

The listed experimental results show that conditional ES grade demonstrates the most intensive resistance to SSCC. 40 and 20N2M steel grades have low k_{tssc} = 0.45-0.60 values (Fig. 3). Signs in Figure 3 correspond to numbers from Table 2. Deviation of σ_{tssc} values is not more than 10%.

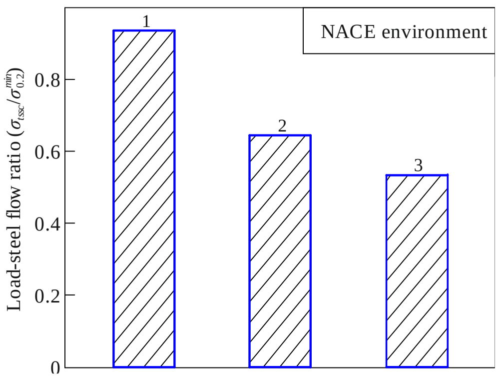

Figure 3. Threshold values of sulfide corrosion resistance under the stress of deep pump rod steel with long-term operation in the NACE environment

In such a way, steel performance for oil rods, assessed using k_{tssc} and σ_{tssc} parameters, differs.

It should be noted that the results of analysis of steel resistance to SSCC correlate well with the data by gravimetric technique of corrosion velocity both in NACE solution and in NaCl solution (Fig. 1).

Consequently, the abovementioned helps conclude that after ES steel, containing low concentrations of harmful sulfur, phosphorus and hydrogen, is modified economically, it is characterized by high resistance to uniform corrosion inclusive of SSCC. Thus, it is applicable for well oil rods.

3.2. HIC analysis

Results of HIC analysis of pump rod metal compared with experimental (where load is not applied) have shown that NACE solution as well as 3% NaCl solution initiates hydrogen cracking and surface swelling of 40 and 20N2M steel grades. Analytical HIC values for the steel types are CLR = 3.2-4.8%; and CTR = 6.9-10.8% which cannot meet the requirements of Specifications [19].

3.3. Analysis of corrosion fatigue (long-term strength)

The following has been obtained during the experiments (Figs. 4-6).

NACE environment, containing hydrogen sulfide, performs more than 4 time decrease in fatigue boundary of samples with 5 mm diameter made from 20N2M steel (i.e. from 380 down to 90 MPa).

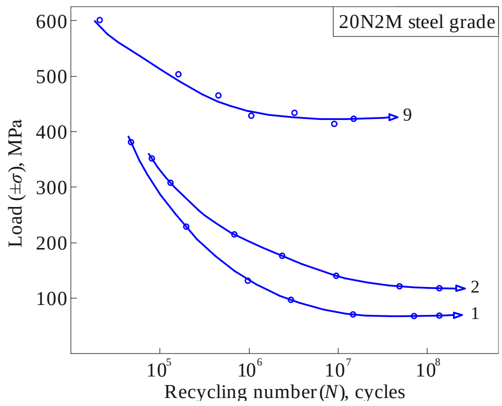

Figure 4. Curves of fatigue (9) and corrosion fatigue (1-2) of rods made of 20N2M steel grade: 1 – in NACE environment; 2 – in 3% NaCl solution with its daily replacement; 9 – in the air

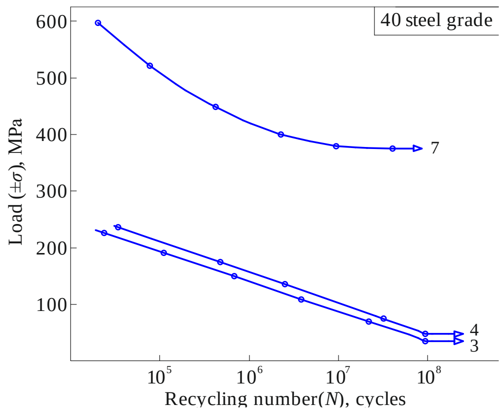

Figure 5. Curves of fatigue (7) and corrosion fatigue (3-4) of rods made of 40 steel grade: 3 – in NACE environment; 4 – in 3% NaCl solution with its daily replacement; 7 – in the air

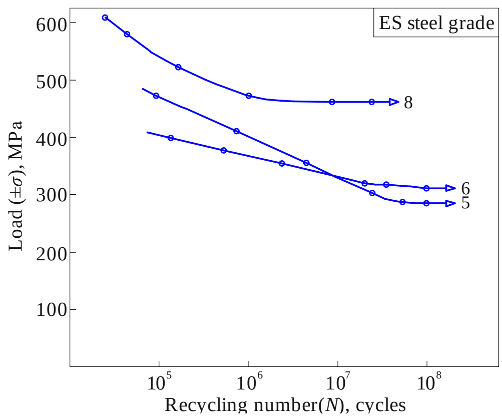

Figure 6. Curves of fatigue (8) and corrosion fatigue (5-6) of rods made of experimental ES steel grade: 5 – in NACE environment; 6 – in 3% NaCl solution with its daily replacement; 8 – in the air

3% NaCl solution, containing no hydrogen sulfide but being oxygen saturated up to 8-10 mg/l concentration performs more than 2.7 times decrease in the fatigue boundary. Conditional strength boundary of steel grade 40 is 50-60 MPa; nevertheless, high stresses reduce durability of samples.

Hydrogen sulfide containing NACE environment performs more than 5 times (i.e. 230 down to 40 MPa) decrease in fatigue boundary of steel grade 40; a 3% oxygen – saturated solution performs more than 4.5 times (220 down to 45 MPa) decrease in the boundary.

Experimental steel demonstrated the highest values of long-term strength both in NACE environment and in NaCl solution. Economical REE modification of steel has helped perform more than 4 times intensification of corrosion fatigue strength even in terms of aggressive NACE environment test as well as 3% NaCl solution as compared to the standard steel of 20N2M grade (Fig. 6). Thus, under 50 cycles, conditional boundary of corrosion fatigue in hydrogen sulfide containing environment (curve *13* in Figure 6; curve *4* in Figure 4; and curve *10* in Figure 5) increased from 40-80 up to 190-280 MPa. In 3% NaCl solution with daily environmental oxygenation increased from 50-140 up to 200-290 MPa (curves *5* and *11* in Figures 4 and 5).

It has been defined that oxygen in the mineralized environment is corrosive agent just as hydrogen sulfide. If 3% NaCl solution is not replaced by a fresh one then corrosion fatigue characteristics intensify visibly (Figs. 4 and 5). The fact is explained by the dissolved oxygen which impoverished significantly the environment during the long-term tests. Boundary hydrogen sulfide saturation of 3% NaCl solution reduces oxygen concentration in the environment; simultaneously, its partial pressure drops. In this connection, corrosive action of the dissolved oxygen comes down while being compensated owing to the growing hydrogen sulfide activity.

The abovementioned experimental results help conclude that positive effect by alloying with the help of modifying impurities is observed consistently if their share in low alloy steel is 0.01-0.03%. Their future increase results in the following. Large particles of cerium silicates contaminate the metal having no influence on the total amount of non-metallic inclusions.

Numerous studies by domestic and foreign researchers note that the decreased resistance to SSCC and HIC of the certain carbon-based and low alloyed steel types may result from silicates as well as micro liquation of some alloying elements or impurities, or disturbances of thermal and mechanical modes while hollow billet and core milling.

Hence, laboratory studies and experiments have shown that the economically modified steel types are characterized by high corrosion fatigue strength; moreover they can be applied for deep pump rods contacting aggressive environments.

Industrial tests of the pilot sets of pump roads, manufactured with the use of 20HM steel modified economically by 0.03% cerium, in oil wells of Naftogaz Ukrainy NJSC have demonstrated that both stability and efficiency are preserved for long-term operation. No corrosion damage and failure has been observed in the pilot rods during more than three-year functioning despite hydrogen penetration and mineralization of well product containing chemically aggressive impurities.

3.4. Metallographic studies

Metallographic analysis has helped identify that pittings initiate at the surfaces of pump rod samples if hydrogen sulfide containing environment and stresses act simultaneously; for the certain period, the pittings transform into cracks. SSCC cracks progress perpendicularly to a direction of metal texturing and load.

At the same time, some areas have demonstrated longitudinal layering, i.e. cracks transversely to which a crack propagates being typical for SSCC in addition to a surface swelling. It is generally accepted that both HIC and steel swelling progress if only external loads are not available. SSCC cracks result from loads [20]. Since, the pilot steel has no tendency to HIC and swelling while being under loads then the results support the idea that external loads stimulate the types of metal destruction of well pump rods. Many scientists and researchers believe [21] that mainly SSCC of experimental pipe, tube, and rod steel, characterized by high viscous-plastic properties and law hardness (HRC $\leq$ 22), may result from high sulfur and phosphorus content, and (or) local formation of acicular structures of martensite-bainitic type.

Our research has not observed any formation of acicular structures in the analyzed steel samples. Study of chemical composition as well as mechanical characteristics of the pilot steel types has shown (Table 1) that only experimental steel (specified as ES) is within the technical requirements of the International Standard (Specification SPC-62900-XP-007) allowing small amount of harmful impurities involving sulfur (up to 0.012%) and phosphorus (up to 0.012%).

All other steel types contain excessive sulfur (0.020-0.039%) and phosphorus (0.021-0.040%) which may initiates formation of sulfide and non-metallic inclusions. As a rule, they are the area where corrosion cracks originate. It should be mentioned that the steel grades are characterized by high concentration of dissolved nitrogen (0.0039-0.0052%). Taking into consideration an absorption theory of metal cracking helps understand that under the effect of the applied stresses in steel, contacting corrosive environment, hydrogen generally diffuses till the defects of crystalline structures or non-metal inclusions (NMIs). Hydrogen adsorption at the surface of the basic metal-NMIs boundary favours breakage of inter-crystalline connections resulting in a microcrack initiation. Stress action increases it up to macrocrack dimensions.

Low hydrogen content in the experimental ES steel, involving REE micro impurities, can be explained as follows.

It is known [22] that REEs are characterized by high thermodynamic activity. Moreover, they have close chemical connections with oxygen, nitrogen, and hydrogen while making rather stable combinations (i.e. oxides, nitrides, and hydrides). In addition, the elements are partially soluble in the molten metal. As for the hydrides, they are insoluble; in the process of steelmaking they are removed to slag. It has been identified that if REE arch is in the atmosphere then a formation reaction of hydroxyl OH ($OH \rightarrow H + O$), being insoluble in the molten metal, shifts to the left resulting in the decreased hydrogen absorption by a metal bath.

High vapour pressure of REEs and their combinations are important for a mechanism decreasing hydrogen content in the metal since they drop partial hydrogen pressure above the molten bath as well as its solubility.

It has been defined that the elements are surfactants. They are adsorbed at the surface, separating crystals, and slow down all processes connected with dislocation displacement while complicating diffusion of hydrogen atoms during metal crystallization. Hence, velocity of hydrogen delivery to places where defects are accumulated decreases which may factor into the improved metal resistance to hydrogen cracking. The findings mean that the alloying components impact heavily the structure representing high sensitivity to the process of damage accumulation as well as local metal failure.

Based upon the obtained numerous results, complex and system studies will help develop practical methods, stipulations, and procedures preventing from corrosion attacks and breakages of well facilities.

The experimental results as well as the proposed solutions may become the scientific basis to develop organizational and technical as well as design-engineering measures suppressing cracks and hydrogen film formation in pipe and tube structures aimed at long-term operation within the corrosive environments with simultaneous action of both internal and external alternate loads at the deposits and at the oil enterprises.

4. Conclusions

Resistance to SSCC, HIC, and corrosion fatigue of steel of deep pump rods for oil industry has been analyzed. It has been identified that experimental steel, modified economically with the help of REE trace components, meets the requirements of NACE MR0175-96 Standard in terms of chemical composition and strength. In turn, 20N2M and 40 steel grades cannot resist heavily to SSCC (threshold stresses are < $0.8 \cdot \sigma^{min}_{0.2}$), and corrosion fatigue destruction. Moreover, 40 steel grade demonstrated low resistance to HIC (CLR > 6% and CTR > 3%).

It has been determined that a source of the corrosion fatigue destruction is hydrogen film formation of a metal surface resulting in its cracking with following destruction under the action of alternate loads accelerated by action of corrosive environment. Further surface microdestruction under the influence of macrostresses progresses into large discontinuities and cracks giving rise to macro destruction.

High resistance to corrosive crack formation is achieved owing to refining of pump rods made from ferrite-perlite steel grades. They are refined using metallurgical methods, i.e. by means of REE microalloying within 0.01-0.03%.

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Дослідження корозійно-втомної міцності сталі насосних штанг нафтових свердловин

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Мета. Порівняльний аналіз корозійно-тривалої міцності (втоми) матеріалів насосних штанг в різних хімічно-активних модельних середовищах та дослідження впливу економно модифікованої рідкоземельної домішки на корозійно-втомну міцність матеріалу штанг.

Методика. Застосовано: сталь марок 40, 20N2M і ЕС (експериментальна сталь). Сталь умовної марки ЕС виплавляли на експериментальній ділянці Інституту електрозварювання імені Є.О. Патона НАН України. Вона економно легувалася мікродомішкою рідкоземельного елементу (РЗЕ) – церієм в кількості 0.03%, крім того містила порівняно низьку концентрацію сірки та фосфору, а також незначну концентрацію розчиненого водню. В якості модельних середовищ використовували: 1) середовище NACE (5%

розчин NaCl, який містив 0.5% CH_3COOH і насичений H_2S; *t* = 22 ± 2ºC; pH = 3.8-4.0); 2) 3%-вий розчин NaCl без сірководню і з періодичною заміною цього середовища один раз на добу з метою під насичення киснем до концентрації 8-10 мг/л.

Результати. Досліджена стійкість проти сульфідного корозійного розтріскування під напруженням (СКРН) та воднем ініційованого розтріскування (ВІР) і корозійної втомності сталей глибинних насосних штанг, призначених для нафтової промисловості. Встановлено, що експериментальна сталь, економно модифікована мікродомішками РЗЕ, задовольняє вимогам стандарту NACE MR0175-96 за хімічним складом і міцністним властивостям, а сталі 20N2M і 40 не мають високого спротиву СКРН (порогові напруження < 0.8 с) і корозійно-втомному руйнуванню, причому сталь 40 показала низький спротив ВІР (CLR > 6% і CTR > 3%).

Наукова новизна. Встановлено, що першопричиною корозійно-втомного руйнування є наводнення поверхні металу, що спричиняє окрихчення і, як наслідок, його руйнування під впливом знакозмінних навантажень, прискорене дією корозійно-активного середовища. В подальшому мікроруйнування поверхні під впливом макронапружень розвиваються в крупні несуцільності і тріщини, які ведуть до макроруйнування.

Практична значимість. Доведено, що висока стійкість проти корозійного розтріскування досягається рафініруванням насосноштангових сталей ферито-перлітного класу металургійними методами – мікролегуванням РЗЕ в межах 0.01-0.03%.

Ключові слова: *корозія, сталь, руйнування, деградація, свердловина, насосні штанги*