Здійснено інженерні оцінки швидкості корозійного руйнування нафтопроводів, що враховує як механічні, так і фізико-хімічні параметри взаємодії деформованого металу з робочим середовищем. Визначено характеристики циклічної корозійної тріщиностійкості металу труби експлуатованих нафтопроводів із урахуванням дії експлуатаційних чинників. Встановлено, що водні корозійні середовища суттєво впливають на процес поширення втомної тріщини у досліджуваних сталях

Ключові слова: нафтопровід, тріщиноподібний дефект, діаграма циклічної корозійної тріщиностійкості, коефіцієнт інтенсивності напружень

Выполнены инженерные оценки скорости коррозионного разрушения нефтепроводов, учитывающие как механические, так и физико-химические параметры взаимодействия деформированного металла с рабочей средой. Определены характеристики циклической коррозионной трещиностойкости металла трубы эксплуатируемых нефтепроводов с учетом действия эксплуатационных факторов. Установлено, что водные коррозионные среды существенно влияют на процесс распространения усталостной трещины в исследуемых сталях

Ключевые слова: нефтепровод, трещиноподобный дефект, диаграмма циклической коррозионной трещиностойкости, коэффициент интенсивности напряжений

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PECULIARITIES OF CORROSION DEGRADATION OF STEEL OF OIL PIPELINES

V. Luzhetskyy
Dr. Eng., Associate Professor
Department of Mechanical Engineering and Technology-based
Ivan Franko Drohobych State Pedagogical University
I. Franko, 24, Drohobych, Ukraine, 82100
E-mail: vaslu@rambler.ru

1. Introduction

Technical diagnostics of responsible constructions exploited in the conditions of combined power load and corrosive aggressive media is an actual scientific and technical problem, particularly, for definition of long-term exploitation objects [1, 2]. Pipes, used for oil production and transportation, are in constant contact with corrosive and deleterious substances which cause intensive internal corrosion of pipes, whereas their abrasion is accompanied with great material losses and severe ecological consequences [3, 4].

As demonstrated by multiple researches [5, 6], processes of wear-out failures of industrial constructions under the influence of combined action of mechanical loadings and corrosive workspaces are caused by a number of physical and chemical localised processes of formation and development of fissuring troubles in the material [6–8]. Besides, alongside with places of enhanced exertion concentration (openings, cuttings, cracks and other technological and constructive exertion raisers), these processes often arise on smooth distorted surfaces, which is due to heterogeneity of their physical and chemical condition [7]. This has been affirmed by the latest statistical data, namely, that almost 80 % of all oil pipelines failures are caused by primary corrosion-mechanical damage (Fig. 1) and by progressing surface fissuring troubles in places of corrosive caverns and welding joints [8]. In this connection, there appears an acute problem in development of effective methods of evaluation of these phenomena and adequate loading diagrams for engineering practice [9].

Thus, definition of features and evaluation criteria of technical state of oil pipelines and the interrelation between parameters of physical-mechanical state of their material and operating environment corrosion mechanisms is an actual scientific and applied engineering task.

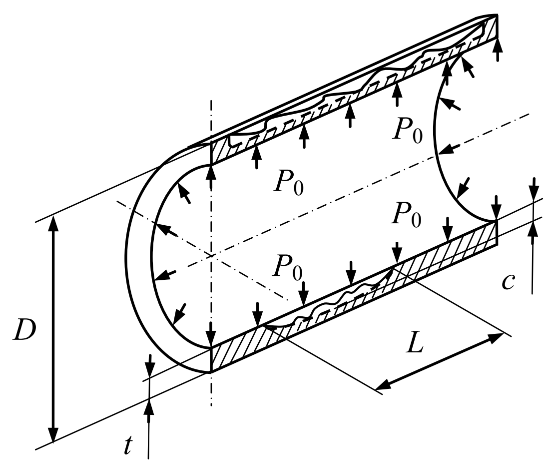


Fig. 1. Schematisation of defects in oil pipelines

2. Analysis of literature data

Various aspects of the problem were studied by domestic and foreign scholars. In the first place, one should note works by I. Dmytrakh [10] and V. Kucheryavyy [11], in which did a theoretical study of the distribution of elastic and elastic-plastic stress at cracks in cylindrical shells. The works of Si-jian Lin [12] offer numerical and analytical methods of calculating stress intensity factors for cracks of various shapes and arrangement in cylindrical bodies under loads that simulate the operational load on the pipeline. The problems of corrosion and corrosion fatigue of pipeline steels are dealt with in the works of A. Marshakova [13] and P. Marcus [14], where physical, chemical and electrochemical fundamentals associated with this problem are provided. G. Nykyforchyn [15] and co-workers proposed a method for evaluating the operational degradation of materials of conduits operated on continuous bases. One should also mention research by E. Kryzhanivskyy [16] that is dedicated to improving oil pipelines' resource.

However, it is necessary to take into account the fact that the destruction of the material under the influence of long-term operating factors is a multistage process and the impact of each step ultimately determines the durability of the pipe element in the given conditions. Therefore, on fundamental importance is subcritical growth of corrosion or crack-like defects caused by the action of compatible operating loads and environments. In existing approaches, these processes are insufficiently studied yet and not taken into account when predicting longevity of pipelines, namely the degradation of physical and mechanical properties of the operated metal.

3. Problem setting

It is possible to prolong durability and provide reliable exploitation of trunk pipelines by diagnosing the actual state of metal and characteristics of its resistance to fissuring troubles expansion, taking into consideration a number of exploitation factors (such as static, cyclic and dynamic loads, corrosive media) which influence probable development of the detected damages [17, 18].

In order to carry out these engineering evaluations, today they use modern approaches to fracture mechanics [19, 20], which enables the definition of regularities of corrosion cracks expansion under the influence of fatigue failures that are represented in the form of cyclic corrosive crack resistance charts, which are dependences of fracture growth rate on stress intensity factor K_I. Such charts are arranged between its two boundary values: bottom threshold value K_{th} corresponding to the value of K_I at which there occurs no corrosive fatigue failure growth, and upper K_{fc} corresponding to the value of K_I at which there occurs spontaneous (catastrophic) growth of a fracture. The average amplitude part of such charts is analytically described by Paris power dependence [21]

$$dc/dN = da/dN = C(\Delta K)^n,$$

where in C and n are system "material – environment" constants, ΔK_I is stress intensity factor ($\Delta K_I = K_{Imax} - K_{Imin}$), definable as a function of working pressure inside a pipe.

The four aforementioned chart parameters (K_{th}, K_{fc}, C and n) are characteristics of cyclic corrosive crack resistance of the oil-trunk pipe material.

4. The purpose and object of research

Grounding on charts of cyclic corrosive crack resistance of the oil-trunk pipeline material to substantiate a comparative evaluation of the influence of corrosive media on corrosive fatigue failures developing in it for different "material – environment" systems.

Our research object, thus, is processes of formation and development of fissuring defects in pipe walls, and the influence of their forms and sizes on a pipe's working capacity.

5. Methods of definition of cyclic crack resistance of a pipe material

The investigations have been carried out for both unused (new) metal (steel 10Г2БТЮ3, $\sigma_{0,2}$=423,7 mPa, δ=26,9 %, d_{ext} =530 mm, t=8 mm) and used metal (steel 10Г2БТЮ3, $\sigma_{0,2}$=438,9 mPa, δ=25,6 %, d_{ext}=530 mm, t=7 mm) of oil pipeline "Druzhba". Also, investigations have been conducted for new metal (steel 20, $\sigma_{0,2}$=355,2 mPa, δ=23,9 %, d_{ext}=273 mm, t=10 mm) and used metal (steel 20, $\sigma_{0,2}$=332,8 mPa, δ=26,2 %, d_{ext}=273 mm, t=9 mm) of oil pipeline "Dolyna – Drohobych". Mechanical characteristics of steel have been defined after a standard testing procedure of cylindrical samples for stretching. In Table 1 chemistry of the investigated steel is presented.

Table 1

Chemistry of steel

Mass content of elements, %								
C	Mn	Si	V	Nb	Al	Ti	S_{max}	P_{max}
steel 10Г2БТЮ3								
0,11	1,68	0,35	0,09	0,03	0,04	0,02	0,006	0,02
steel 20								
0,19	0,48	0,29	0,23	0,25	0,24	0,08	0,040	0,035

All basic physico-mechanical investigations of corrosive fatigue failures developments have been conducted on prismatic models. The intermediates for samples of 10 mm×t×40 mm in size have been cut out from fragments of real pipes. The total length of the sample add up to l=200 mm.

The diagrams of cycle crack resistance of unused metal of the pipeline have been received by way of testing of approbation beam samples with rectangular section with the initial edge crack c=1,5...2,0 mm.

Investigations have been conducted of cyclic crack resistance of used metal of an over 80 km long "Druzhba" oil-trunk pipeline segment, which have been in operation for 41 year. What should be underlined is, that as a result of metal abrasion during operation process the thickness of the pipe wall lessened from 8 mm to 7 mm, and the most typical operational defects are corrosion defects, caused by joint action on metal of working loadings and environments.

Also, investigations have been conducted of cyclic crack resistance of used metal of an about 60 km long "Dolyna – Drohobych" oil-trunk pipeline segment, which have been in operation for 42 year. What should be underlined is, that as a result of metal abrasion during operation process the thickness of the pipe wall lessened from 10 mm to 9 mm.

The investigations for cyclic crack resistance have been conducted on special experimental equipment in pure bend conditions of the models with 1 Hz frequency at the sinusoidal form of loading cycle (R≈0,8). They have been tested in laboratory air, in distilled water (pH 6,7), as well as in 0,1 % NaCl solution (pH 6,5), which served as a soil water model. Environment temperature T=25 °C.

The models have been tested to final fracture with the subsequent analysis of fracture surfaces. The computerized fracture surface images, that correspond to different stages of corrosive fatigue failures development, can be used as models at identification of fracture conditions of real elements of pipelines in operation.

For the aforementioned steel 10Г2БТЮ3 and steel 20 test conditions, there in Table 2 the values of constants in Paris power dependence [21] are presented.

Table 2

Characteristics of cyclic crack resistance of steel

System "material – environment"	n	C, m/cycle× ×(mPa·m½)-n	ΔKth, mPa·m½	Kfc, mPa·m½
steel 10Г2БТЮ3				
New metal – air	3,55	5,86 10^{-13}	11,57	43,75
New metal – distilled water	6,76	1,03 10^{-16}	9,90	36,85
New metal – model soil water	7,53	1,63 10^{-17}	9,47	35,51
Used metal – air	4,56	2,61 10^{-14}	10,28	42,90
Used metal – distilled water	8,38	3,00 10^{-18}	8,37	32,62
Used metal – model soil water	10,40	7,36 10^{-21}	7,64	33,61
steel 20				
New metal – air	3,20	4,94 10^{-12}	10,75	36,69
New metal – distilled water	6,10	3,11 10^{-15}	9,61	33,67
New metal – model soil water	6,89	3,02 10^{-16}	8,19	32,24
Used metal – air	4,40	2,36 10^{-13}	6,98	33,70
Used metal – distilled water	8,93	1,28$10^{-18}$	6,62	29,63
Used metal – model soil water	10,28	7,64 10^{-20}	6,24	30,08

Here, also, the corresponding values of threshold (K_{th}) and critical (K_{fc}) stress intensity factors are given.

6. Investigation results

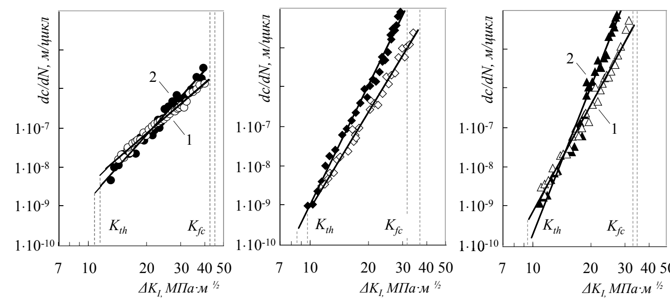
Approbation results have been represented as diagrams of cyclic crack resistance. These diagrams for various testing media for new and used metal are shown in Fig. 2, *a–c)* and Fig. 3, *a–c*.

The analysis of the final results testifies to the following. With the growth of test media corrosiveness (laboratory air – distilled water – soil water), cyclic crack resistance of both new and used metal declines.

For all analysed cases the cyclic crack resistance of used metal of oil pipelines is lower, than for the metal of the new pipe. The exploited metal is more sensitive to the environmental influence.

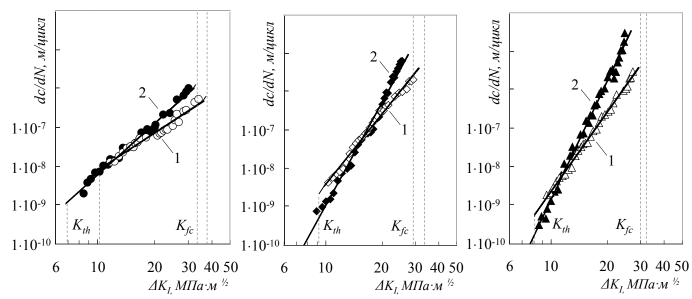
In particular, during the tests of used steel in soil water, the value of exertion intensity factor K_{th} declines in 1,5–1,7 times, whereas critical value K_{fc} declines in 1,3–1,6 times in comparison with the analogical data for new metal in the air.

Thus, we have defined the degree of influence of aggressive corrosive media on propagation of fatigue failure in the indicated steel.



a *b* *c*

Fig. 2. Influence of operational medium on cycle crack resistance diagram for new (1) and used (2) metal (steel 10Г2БТЮ3) of "Druzhba" oil-trunk pipeline: *a* — laboratory air; *b* — distilled water; *c* — soil water



a *b* *c*

Fig. 3. Influence of operational medium on cycle crack resistance diagram for new (1) and used (2) metal (steel 20) of "Dolyna — Drohobych" oil pipeline: *a* — laboratory air; *b* — distilled water; *c* — soil water

7. Conclusion

New data on character and peculiarities of fatigue and corrosive fatigue failure of pipes in dependence on the initial size and form of the detested in the pipeline defects have been obtained.

It has been established, that the exploited over 40 years (degraded) metal of "Druzhba" oil-trunk pipeline (steel 10Г2БТЮ3) in corrosion medium has smaller resistance to propagation of cracks in comparison with unused metal.

The obtained results showed a significant decrease in performance rather cyclic crack exploited metal trunk pipeline "Dolyna – Drohobych" compared to new metal. For example, when tested in air threshold (ΔK_{th}) stress intensity factors differ by more than 30 %.

It has also been found out, that aquatic corrosive media (soil and distilled water) essentially influence the process of a fatigue failure propagation in steel 10Г2БТЮ3 and steel 20. The most dangerous corrosive medium is 0,1 % NaCl solution, that is, model soil water.

8. Practical importance of the results

With the purpose of determination of the mechanism of corrosive-mechanical damages and developing of the recommendations for their preventive maintenance, the data obtained on cyclic crack resistance a pipe material will further be used in computed estimations of durability and longevity of pipeline elements taking into account the subcritical development of corrosion fissuring defects.

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