МЕХАНИКА ДЕФОРМИРУЕМОГО ТВЕРДОГО ТЕЛА

UDC 539.4

VESELUKHA Vadim M., Ph. D. in Eng.
Lecturer of Special Disciplines[1]
E-mail: vad-777@mail.ru

BOGDANOVICH Alexander V., D. Sc. in Eng., Assoc. Prof.
Professor of the Department of Theoretical and Applied Mechanics[2]
E-mail: bogal@tut.by

[1]Lida College of the State University of Grodno named after Yanka Kupala, Lida, Republic of Belarus
[2]Belarusian State University, Minsk, Republic of Belarus

Received 28 November 2019.

ON THE METHOD OF EXPERIMENTAL EVALUATION OF MODEL PARAMETERS FOR PREDICTING THE CHARACTERISTICS OF PIPE MATERIAL CRACK RESISTANCE, TAKING INTO ACCOUNT THE INFLUENCE OF CORROSION-EROSION PROCESSES

The article considers the peculiarities of the model for predicting the crack resistance characteristics of pipe material taking into account the influence of corrosion-erosion processes during long-term operation with an estimation of one of the major characteristics of cyclic crack resistance, threshold stress intensity factor. A methodical description is given for the experimental determination of the values of cyclic crack resistance characteristics (threshold stress intensity factor, parameters of Paris equation of fatigue fracture kinetic diagram) of the pipe material under the direct corrosion-erosion effect of a liquid medium on fatigue crack front in laboratory compact specimen.

Keywords: *crack resistance, survivability, pipeline, stress intensity factor, tightening, corrosion-erosion processes*

Introduction. An experimental determination of the crack resistance characteristics of structural elements and laboratory specimens is carried out in accordance with long-established recommendations [1] under cyclic, standard [2], static loading, and also only for oil pipes, the new standard of the Republic of Belarus [3], in the air, other gaseous and inert media, as well as in vacuum. However, in case of structural element working in liquid media, new problems arise due to the interaction of the material, i.e. medium, which can have a significant impact on the crack growth resistance [4].

When studying the characteristics of crack resistance in inert media, the dominant mechanism of local material destruction in the vicinity of the crack tip is the mechanical process of fatigue (or static) destruction. Therefore, the stress intensity factor (SIF) as a parameter of linear fracture mechanics fully controls the fracture process. Each of its values will correspond to a certain rate of crack growth. When testing for crack resistance in liquid media, especially corrosive ones, the mechanical failure factor loses its dominant value as a result of physical and chemical processes at the crack tip between the material and the medium. These processes, which depend on the state of the fracture surface and occur at different speeds, also affect the formation of the prefracture zone at the crack tip. Therefore, the crack growth rate will be determined not only by the SIF, but also by the parameters characterizing the physicochemical processes at the crack tip between the material and the medium, as well as the parameters characterizing the fracture surface [4, 5].

The task of estimating the characteristics of resistance to crack growth of structural materials, including pipe steels of main oil and gas pipelines, pipelines of chemical enterprises and conventional water pipes, in conditions of exposure to liquid corrosive media is very relevant.

This work determines the method of experimental determination of model parameters for predicting changes in crack resistance characteristics of pipe steel material in conditions of corrosion-erosion effects of any liquid media.

A model for predicting changes in the crack resistance characteristics of pipe material taking into account the effect of corrosion-erosion processes. Numerous experiments have shown that a liquid medium, especially a corrosive one, not only increases the growth rate of the fatigue crack, but also changes the nature of the fatigue fracture diagram itself. Thus, in the most general case of interaction of corrosive fatigue and stress corrosion processes, the fatigue fracture diagram opposed to an inert medium (Figure 1, curve 1), has the form shown by curve 2 in Figure 1, which can significantly change depending on the loading parameters, metal structure, physical and chemical properties of the medium [4, 6–8].

Previously [9] there was given a description of model elements for forecasting crack resistance characteristics of pipe material taking into account the effect of corrosion-erosion processes during long-term operation. Below we will briefly consider the method of estimation of one of the most important characteristics of cyclic crack resistance, the threshold SIF, according to this model.

Based on the assumption that the endurance limit is the minimum stress at which cracks begin to develop, the size l_{c*} of which is a constant value for the given material, then the value of the threshold SIF can be estimated by the expression [10]:

$$K_{\max th} = Y\sigma_{-1}\sqrt{\pi l_{c*}}, \qquad (1)$$

where l_{c*} — the critical size of microcracks; Y — the correction factor, which is taken equal to 0.65 for a surface crack in the form of a semicircle and 1.12 for a surface crack passing through the entire thickness of the specimen.

Let's write down the formula (1) for the threshold SIF taking into account the effect of corrosion-erosion processes in the form:

$$K_{\max th(ch)} = Y\sigma_{-1\tau(ch)}\sqrt{\pi l_{c*}}, \qquad (1a)$$

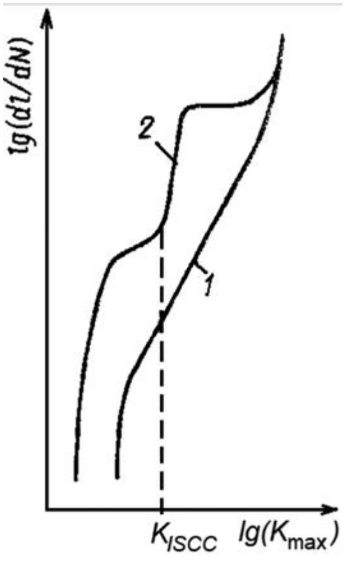

Figure 1 — Typical kinetic diagrams of fatigue fracture in an inert (1) and liquid (2) medium

where $\sigma_{-1\tau(ch)}$ is the endurance limit taking into consideration the effect of friction and corrosion erosion, the value of which can be estimated by the expression:

$$\sigma_{-1\tau(ch)} = \sigma_{-1} \cdot \varphi(\tau_L, D_\tau), \qquad (2)$$

where the function of the influence of tangential stresses and friction corrosion

$$\varphi(\tau_L, D_\tau) = \sqrt{\frac{1}{\Lambda_{\sigma/\tau}} - \left(\frac{\tau_L}{\tau_{ec}}\right)^2 \left(\frac{\upsilon_{ch}(\tau)}{\upsilon_{ch}}\right)^{m_\upsilon(\tau)}} \qquad (3)$$

is determined not only by the level of tangential stresses $(\tau_L/\tau_{ec}) < 1$ (here τ_{ec} is the limit of corrosion-erosion fatigue of the inner surface of the pipe in the absence of normal, stretching or bending, stress σ), but also by the parameter $\Lambda_{\sigma/\tau} \gtreqless 1$, describing the conditions and direction of dialectical interaction of mutually conditioned damages from normal and tangential stresses.

Tangential stresses τ_L can be determined by the already known formula [11–13]:

$$\tau_L = f_L \rho_L \upsilon_L^2 / 2, \qquad (4)$$

where f_L — the parietal friction coefficient; ρ_L — the density of the pumped product; υ_L— the flow rate of liquid in the pipe.

In the formulas (2) and (3), parameters D determine the contribution of corrosion processes to complex damage to pipe material [11–13]:

$$1 - D_\sigma = \left(\frac{\upsilon_{ch}}{\upsilon_{ch(\sigma)}}\right)^{m_{\upsilon(\sigma)}}; \quad 1 - D_\tau = \left(\frac{\upsilon_{ch}}{\upsilon_{ch(\tau)}}\right)^{m_{\upsilon(\tau)}}, \qquad (5)$$

where υ_{ch} is the corrosion rate in a given medium; $\upsilon_{ch(\sigma)}$, $\upsilon_{ch(\tau)}$ are the corrosion rate in the same medium, respectively, under power (index σ), friction (index τ) impacts; m_v is the parameters determining the electrochemical activity of materials under power (index σ) and friction (index τ) loadings.

According to (2) and (3) we have

$$\sigma_{-1\tau(ch)} > \sigma_{-1},$$

when $\varphi(\tau_L, D_\tau) > 1$ and, consequently, $\Lambda_{\sigma/\tau} < 1$, and also

$$\sigma_{-1\tau(ch)} < \sigma_{-1},$$

when $\varphi(\tau_L, D_\tau) < 1$ and, consequently, $\Lambda_{\sigma/\tau} > 1$.

Hence, the threshold SIF of the pipe's inner surface material after long-term operation under the influence of corrosion and erosion processes depends on:

- level of conventional (σ), tangential (τ_L) stresses and corrosion environment effect (D_σ, D_τ);
- critical size of microcracks (l_{c*});
- pipe material strength under the specified influences ($\sigma_{-1\tau(ch)}$, τ_f, m_υ, υ_{ch});
- interaction of damages caused by mechanical fatigue and friction ($\Lambda_{\sigma/\tau}$).

Apparently, the size of microcracks l_{c*} in the expression (1a) for the pipe material should be different from that one in the air and due to the influence of corrosion-erosion processes.

Thus, the threshold SIF for the material of the pipe in which the liquid corrosive medium moves:

$$K_{\max th(ch)} = \varphi_{K(ch)} \cdot K_{\max th}, \tag{1b}$$

where $\varphi_{K(ch)}$ — the function of the influence of corrosion-erosion processes; $K_{\max th}$ — the threshold SIF of pipe material in air.

Similarly, for the constants C and m of the Paris equation describing the middle section of the fatigue fracture kinetic diagram, there can be written:

$$C_{(ch)} = \varphi_{C(ch)} \cdot C, \tag{6}$$

$$m_{(ch)} = \varphi_{m(ch)} \cdot m, \tag{7}$$

where $\varphi_{C(ch)}$, $\varphi_{m(ch)}$ are the influence functions of the corrosion-erosion processes; C and m are the constants of the fatigue fracture kinetic diagram of the pipe material in the air.

Experimental estimation of parameters. Since the calculated estimation of the values of the functions $\varphi_{K(ch)}$, $\varphi_{C(ch)}$, $\varphi_{m(ch)}$ of the influence of corrosion-erosion processes is currently difficult, we can propose a method for their experimental determination.

Figure 2 shows a scheme for testing a compact specimen of the studied structural material for crack resistance in liquid media. Sample 1 is fixed by means of devices 2 in the grips 3 of the testing machine inside the test chamber 4 and loaded with the force P. The crack growth is recorded by the crack opening sensor 5 installed on the specimen (in a sealed version). Chamber 4 is filled with a working liquid (corrosive) medium; in this case, devices can be installed to control and maintain the required pH value.

The process of loading and processing of experimental data is carried out in accordance with [1, 3]. To conduct special studies of the erosion factors effect on the crack resistance parameters of the pipe material it is easy to provide additional forced circulation of the working liquid (corrosive) medium at a given rate υ_L through the test chamber near the fatigue crack front in the specimen.

It should be noted that carrying out laboratory tests according to the scheme shown in the Figure 2 is reasonable for the pipe material under cyclic loading at low crack growth rates ($1 \cdot 10^{-10} \ldots 1 \cdot 10^{-8}$ m/cycle) when the influence of corrosive medium is especially high.

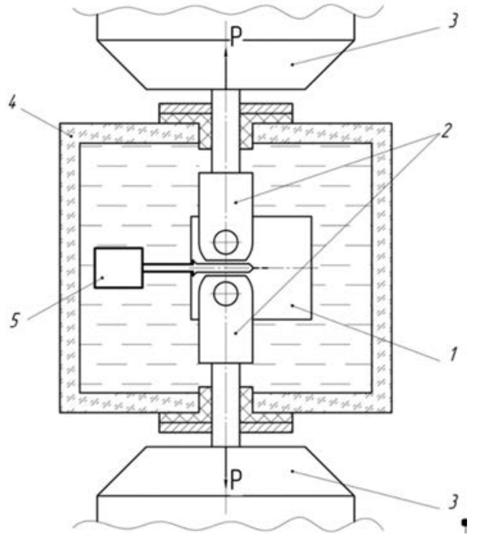

Figure 2 — Scheme of testing structural materials for crack resistance in liquid media: 1 — specimen; 2 — device for fixing the specimen; 3 — grips of the testing machine; 4 — test chamber; 5 — crack opening sensor

Conclusion. Thus, the peculiarities of the proposed model are considered for predicting the crack resistance characteristics of the pipe steel material taking into account the influence of corrosion-erosion processes during long-term operation with estimation of one of the most important characteristics of cyclic crack resistance, threshold SIF. Using the test scheme presented in the Figure 2, it is proposed to empirically determine the values of cyclic crack resistance characteristics, in particular, $K_{\max th(ch)}$, $C_{(ch)}$, $m_{(ch)}$ for pipe material in a given corrosive environment. If the values of the corresponding characteristics ($K_{\max th}$, C and m) in the air are previously experimentally established, then it is easy to find the values $\varphi_{K(ch)}$, $\varphi_{C(ch)}$, $\varphi_{m(ch)}$ of the influence functions of corrosion-erosion processes (see expressions (5)–(7)). In addition, tests in the aggressive environment make it possible to improve the accuracy of the established values of characteristics, especially in the near-threshold crack growth areas.

References

1. Opredelenie kharakteristik treshchinostoykosti (vyazkosti razrusheniya) pri staticheskom nagruzhenii [Determination of crack resistance characteristics (fracture toughness) under static loading]. *Metodicheskie rekomendatsii MR 1-95. Mekhanika katastrof. Opredelenie kharakteristik treshchinostoykosti konstruktsionnykh materialov* [Methodical recommendations MR 1-95. Mechanics of disasters. Determination of crack resistance characteristics of structural materials], 1995, pp. 7–82.
2. State Standard 25.506-85. *Opredelenie kharakteristik treshchinostoykosti (vyazkosti razrusheniya) pri staticheskom nagruzhenii* [Determination of crack resistance characteristics (fracture toughness) under static loading]. Moscow, Standartov Publ., 1985. 42 p.
3. Standard of Belarus 2502-2017. *Truby nefteprovodnye. Metody ispytaniya trubnoy stali na treshchinostoykost (Standart Belarusi)* [Oil pipeline pipes. Methods of testing pipe steel for crack resistance (Standard of Belarus)]. Minsk, Gosstandart Publ., 2017. 29 p.
4. Panasyuk V.V., Ratych L.V., Dmytrakh I.N. O nekotorykh metodicheskikh osobennostyakh issledovaniya tsiklicheskoy treshchinostoykosti konstruktsionnykh materialov v zhidkikh sredakh [Some methodological features of the study of cyclic crack resistance of structural materials in liquid media]. *Materialy VI Mezhdunarodnogo kollokviuma "Mekhanicheskaya ustalost metallov"* [Proc. 6 International colloquium "Mechanical fatigue of metals"]. Kiev, 1983, pp. 284–292.
5. Sosnovskiy L.A., Makhutov N.A. Korrozionno-mekhanicheskaya ustalost: pryamoy i obratnyy effekty (obobshchayushchaya statya) [Corrosion-mechanical fatigue: direct and reverse effects (summary article)]. *Zavodskaya laboratoriya* [Industrial Laboratory], 1993, vol. 59, no. 7, pp. 33–44.
6. *Corrosion Fatigue: Chemistry, Mechanics and Microstructure.* Houston, National Association of Corrosion Engineers, 1972. 762 p.
7. Vosikovski R. Rost ustalostnoy treshchiny v truboprovodnoy stali Kh-65 pri ispytaniyakh s nizkoy chastotoy tsiklov v solenoy i presnoy vode [Fatigue crack growth in pipeline steel X-65 during tests with low cycle frequency in salt and fresh water]. *Teoreticheskie osnovy inzhenernykh raschetov* [Theoretical foundations of engineering calculations], 1975, no. 4, pp. 12–20.
8. Tokano T., Okamura H. Fatigue crack propagation in aqueous environments. *Proc. International Conference on Fracture Mechanics and Technology.* Hong Kong, 1977, vol. 1, pp. 669–712.
9. Veselukha V.M., Bogdanovich A.V. Metodika otsenki ostatochnogo resursa trub lineynoy chasti nefteprovoda s tipichnymi defektami po kriteriyu treshchinostoykosti v usloviyakh tsiklicheskogo nagruzheniya [Method of assessment of the residual life of pipes of the linear part of the pipeline with the typical defects according to the crack resistance criteria under cy-

clic loading]. *Mekhanika mashin, mekhanizmov i materialov* [Mechanics of machines, mechanisms and materials], 2017, no. 2(39), pp. 5–11.

10. Sosnovskiy L.A. *Statisticheskaya mekhanika ustalostnogo razrusheniya* [Statistical mechanics of fatigue failure]. Minsk, Nauka i tekhnika Publ., 1987. 288 p.
11. Sosnovskiy L.A., Kozik A.N. Metodika raschetno-eksperimentalnoy otsenki korrozionno-mekhanicheskoy prochnosti tribofaticheskikh sistem [Method for calculating and experimental evaluation of the corrosion-mechanical strength of tribofatigue systems]. *Mekhanika mashin, mekhanizmov i materialov* [Mechanics of machines, mechanisms and materials], 2011, no. 3(16), pp. 49–53.
12. Sosnovskiy L.A., Kostyuchenko A.A., Vorobev V.V. Inzhenernaya model korrozionno-mekhanicheskoy prochnosti [Engineering model of corrosion-mechanical strength]. *Vestsi Natsiyanalnay akademii navuk Belarusi. Seryya fizika-tekhnichnykh navuk* [Proceedings of the National Academy of Sciences of Belarus. Physical-Technical Series], 2008, no. 2, pp. 66–70.
13. Sherbakov S.S., Sosnovskiy L.A *Mekhanika tribofaticheskikh sistem* [Mechanics of tribo-fatigue systems]. Minsk, Belorisskiy gosudarstvennyy universitet Publ., 2011. 407 p.

В.М. ВЕСЕЛУХА, канд. техн. наук
преподаватель спецдисциплин[1]
E-mail: vad-777@mail.ru

А.В. БОГДАНОВИЧ, д-р техн. наук, доц.
профессор кафедры теоретической и прикладной механики[2]
E-mail: bogal@tut.by

[1]Лидский колледж УО «Гродненский государственный университет им. Янки Купалы», г. Лида, Республика Беларусь
[2]Белорусский государственный университет, г. Минск, Республика Беларусь

Поступила в редакцию 28.11.2019.

О МЕТОДИКЕ ЭКСПЕРИМЕНТАЛЬНОЙ ОЦЕНКИ ПАРАМЕТРОВ МОДЕЛИ ДЛЯ ПРОГНОЗИРОВАНИЯ ХАРАКТЕРИСТИК ТРЕЩИНОСТОЙКОСТИ МАТЕРИАЛА ТРУБ С УЧЕТОМ ВЛИЯНИЯ КОРРОЗИОННО-ЭРОЗИОННЫХ ПРОЦЕССОВ

В статье рассмотрены особенности модели для прогнозирования характеристик трещиностойкости материала труб с учетом влияния коррозионно-эрозионных процессов при длительной эксплуатации с оценкой одной из важнейших характеристик циклической трещиностойкости — порогового коэффициента интенсивности напряжений. Дано методическое описание экспериментального определения значений характеристик циклической трещиностойкости (порогового коэффициента интенсивности напряжений, параметров уравнения Пэриса кинетической диаграммы усталостного разрушения) материала труб при непосредственном коррозионно-эрозионном воздействии жидкой среды на фронт усталостной трещины в лабораторном компактном образце.

Ключевые слова: *трещиностойкость, живучесть, трубопровод, коэффициент интенсивности напряжений, утяжка, коррозионно-эрозионные процессы*

Список литературы

1. Определение характеристик трещиностойкости (вязкости разрушения) при статическом нагружении / Механика катастроф. Определение характеристик трещиностойкости конструкционных материалов. Методические рекомендации МР 1-95. — М.: Изд. МИБСТС, Ассоциация КОДАС, 1995. — С. 7–82.
2. Расчеты и испытания на прочность. Методы механических испытаний металлов. Определение характеристик трещиностойкости (вязкости разрушения) при статическом нагружении: ГОСТ 25.506-85. — Введ. 01.01.1986. — М.: Изд-во стандартов, 1985. — 42 с.
3. Трубы нефтепроводные. Методы испытания трубной стали на трещиностойкость. СТБ 2502-2017. — Введ. 01.10.2017. — Минск: Госстандарт, 2017. — 29 с.
4. Панасюк, В.В. О некоторых методических особенностях исследования циклической трещиностойкости конструкционных материалов в жидких средах / В.В. Панасюк, Л.В. Ратыч, И.Н. Дмытрах // Механическая усталость металлов: материалы VI Междунар. коллоквиума. — Киев: Наук. думка, 1983. — С. 284–292.
5. Сосновский, Л.А. Коррозионно-механическая усталость: прямой и обратный эффекты (обобщающая статья) / Л.А. Сосновский, Н.А. Махутов // Заводская лаборатория. — 1993. — № 7, Т. 59. — С. 33–44.
6. Corrosion Fatigue: Chemistry, Mechanics and Microstructure. NACE-2. — Houston. Texas, 1972. — 762 p.
7. Восиковски, Р. Рост усталостной трещины в трубопроводной стали Х-65 при испытаниях с низкой частотой циклов в соленой и пресной воде / Р. Восиковски // Теоретические основы инженерных расчетов. — 1975. — № 4. — С. 12–20.
8. Tokano, T. Fatigue crack propagation in aqueous environments / T. Tokano, H. Okamura // Proc. Int. Conf. Fract. Mech. and Technol. — 1977. — Vol. 1. — Pp. 669–712.
9. Веселуха, В.М. Методика оценки остаточного ресурса труб линейной части нефтепровода с типичными дефектами по критерию трещиностойкости в условиях циклического нагружения / В.М. Веселуха, А.В. Богданович // Механика машин, механизмов и материалов. — 2017. — № 2(39). — С. 5–11.
10. Сосновский, Л.А. Статистическая механика усталостного разрушения / Л.А. Сосновский. — Минск: Наука и техника, 1987. — 288 с.
11. Сосновский, Л.А. Методика расчетно-экспериментальной оценки коррозионно-механической прочности трибофатических систем / Л.А. Сосновский, А.Н. Козик // Механика машин, механизмов и материалов. — 2011. — № 3(16). — С. 49–53.
12. Сосновский, Л.А. Инженерная модель коррозионно-механической прочности / Л.А. Сосновский, А.А. Костюченко, В.В. Воробьев // Весці НАНБ. Серыя фіз.-тэхн. навук. — 2008. — № 2. — С. 66–70.
13. Щербаков, С.С. Механика трибофатических систем / С.С. Щербаков, Л.А. Сосновский. — Минск: БГУ, 2011. — 407 с.