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PREDICTION OF TRANSPORT VEHICLES' DURABILITY WITH CONSIDERATION OF CORROSIVE SURFACE CRACKS PROPAGATION IN STRUCTURAL ELEMENTS

Summary. Support frameworks of transport vehicles operate under varying terrain conditions under the influence of extreme climate and corrosive environments. When transporting cargo, dust is deposited on the surface of metal structures. The combination of dust and moisture creates an aggressive environment resulting in intense corrosion damage. The damage is caused by the defects of corrosion pitting, which occur on the surface and transform into corrosion cracks. Based on energy approaches, with the application of well-known results for the mathematical description of electrochemical reactions and the principles of fragile fracture mechanics, an analytical model of durability is proposed for the first time. The model determines the residual life of maximum loaded elements of undercarriages with surface cracks under the action of dynamic loads and corrosive environments. For this case, a set of mathematical relations in the form of a non-linear differential equation was developed, as well

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as the initial and final conditions for determining the life of vehicles' structural elements with corrosive surface cracks. The analytical model implementation is proven by solving the problem of determining the residual life of a vehicle's element, i.e., a steel plate, weakened by a semi-elliptical surface crack, which is under the action of dynamic loads in a 3% sodium chloride solution. The insignificant increase in the crack's initial size is proven to greatly reduce the period of its subcritical growth. The developed model was applied to define the residual life of thin-walled elements of structures with surface cracks.

Keywords: elements of structures with surface cracks; kinetic diagram of corrosion-fatigue crack propagation; period of subcritical growth of corrosion-fatigue cracks; durability of vehicle

1. INTRODUCTION

Transport vehicles operate under varying terrain conditions involving extreme climate and corrosive environments. For this reason, their main bearing elements are mainly made of steel. In most vehicular structures, the base unit is a frame that contains up to 40% of the steel intensity of the vehicle and significantly affects its life, with the key factor affecting durability being the damage to the frame caused by cracks and corrosion [1]. Factoring in the volumes of fertilizers transportation (about 2% of all cargo in Ukraine [18]), it is rational to account for the influence of aggressive environments acting upon metal materials of vehicles. When transporting fertilizers, poisonous chemicals and other aggressive agrarian products, the dust of these substances is deposited on the structure surface. The combination of dust and moisture creates an aggressive environment, which, together with the operating loads (usually cyclic), leads to intense corrosion damage, in particular, by propagating surface corrosion-fatigue cracks in elements of vehicular structures [1-8, 14-22]. The corrosion processes rate is known to be a function of the aggressiveness and duration of the environment effect, the air temperature, the metal surface state (composition and structure of the protective film), the chemical composition of the metal, the presence of mechanical stresses, structural features (welds, bolt and rivet joints), and the combination of elements creating cavities or cracks, in which moisture condenses. Contamination of vehicles' metal structure surfaces intensifies corrosion, while, in combination with moisture, it can create an electrochemical environment that causes more intensive corrosion processes. Corrosion is the most dangerous phenomenon for parts operating under cyclic loads (springs, body springs, axes, shafts etc.), whose lifetime is often reduced by 40-60% because of fatigue failure [1,8,12,15,21]. Based on part failure analyses, fracture initiation occurs due to the ulcers caused by corrosion and pitting, with the ulcers transferring into surface corrosion cracks, which adversely affect vehicle reliability [1,12,13,15,21].

2. MATERIAL AND METHODS

A three-dimensional body is considered as an element of the vehicle metal structure. A flat surface crack with a contour of a length L and an initial area S_0 weakens the body, which is loaded cyclically with the amplitude forces *p*. There is a corrosive-aggressive environment in the crack cavity (Figure 1). Outer tensile loads are applied so that the stress-strain state in this body is symmetrical, relative to the placement of a crack plane.

Fig. 1. Corrosion-fatigue cracks in the vehicle frame, a classical body scheme of loading a body with a flat surface crack

Hence, it is described in the vicinity of its peak exclusively by the stress intensity factor of the first kind K_I. The task is to determine the time or number of load cycles $N = N_*$, in which the body, as an element of the vehicle metal structure, will fracture.

To solve this problem, a mathematical model is developed: differential equations with initial and finite conditions that describe this process. The assumption that the crack increases continuously from the original area $S = S_0$ to the final one $S = S_*$ is correct, since it is well known that the real development of the corrosion-fatigue crack is accompanied by jumps in the value ΔS_c in relatively large time intervals Δt_c ($\Delta t_c = T\Delta N$, where ΔN is the number of load cycles during an elementary jump of the crack and T is the cycle period). Thus, the dependence for determining the growth rate of the crack will be written approximately.

$$V = \frac{dS}{dt} \approx \frac{\Delta S_c}{\Delta t_c} \tag{1}$$

Similar to [8-11], the energy balance equation for this non-equilibrium process is:

$$Q + A = W + \Gamma + K \tag{2}$$

where $Q = const$ is the value of thermal energy, A is the work of external forces, and W is the energy of body deformation after the propagation of the crack area by the value ΔS_c, written according to [8-11].

$$W = W_s + W_p^{(1)}(S) + W_p^{(2)}(t) - W_p^{(3)}(t) \tag{3}$$

where: W_s is the elastic component W; $W_p^{(1)}(l)$ is a part of the work of plastic deformations in the prefracture area, which depends exclusively on the area of the crack l; $W_p^{(2)}(t)$ is a part of the work of plastic deformations caused by external forces, which is allocated at a constant crack area during the incubation period of its jump preparation and depends only on time t; $W_p^{(3)}(t)$ is the work of plastic deformations during body unloading and compression of the prefracture area, which depends exclusively on and generates by the body itself; Γ is the energy of body destruction, which depends on the crack area, characteristics of the environment and t; Q is the released thermal energy during body destruction, which is considered a relatively small value and neglected in calculations; and *K* is the kinetic energy, which in this case is also considered a small value.

Considering the above and differentiating the components of the energy balance equation (2) by the number of load cycles *N*, an equation for the velocities balance of the energy components change is deduced:

$$\frac{\partial A}{\partial N} = \frac{\partial W}{\partial N} + \frac{\partial \Gamma}{\partial N} \tag{4}$$

The components of the dependence for determining the energy of deformation are complex functions in *S* and *N* [9-10], while the area also implicitly depends on *N*. Thus, while substituting 3 for 4, the following formula is developed:

$$\frac{\partial}{\partial S}\left[\Gamma - \left(A - W_s - W_p^{(1)} - W_p^{(2)}\right)\right]\frac{dS}{dN} - \frac{\partial W_p^{(3)}}{\partial N} + \frac{\partial \Gamma}{\partial N} = 0 \tag{5}$$

Based on (5), the rate value of the crack area changes during its propagation:

$$\frac{dS}{dN} = \frac{\partial\left(W_p^{(3)} - \Gamma\right)}{\partial N} \Big/ \frac{\partial}{\partial N}\left[\Gamma - \left(A - W_s - W_p^{(1)} - W_p^{(2)}\right)\right] \tag{6}$$

Based on [10, 11], (6) is written thus:

$$\frac{dS}{dN} = \frac{\partial\left(W_p^{(3)} - \Gamma\right)}{\partial N} \Big/ \left(\gamma_{fC} - \gamma_t\right) \tag{7}$$

To complete this mathematical model, in analogy with [10-11], respectively, the initial and final conditions are added to 7:

$$\begin{gathered} N = 0, \quad S(0) = S_0 \\ N = N_*(T), \quad S(N_*) = S_* \end{gathered} \tag{8}$$

where the critical value of the crack area S_* and γ_{fC}, γ_t are determined [10-11].

$$\gamma_t(S_*) = \gamma_{fC}, \; \gamma_{fC} = \sigma_0 \delta_{fC}, \; \gamma_t = \sigma_0 \int_L \delta_{t\,max}^2(s)\,ds \left[\int_L \delta_{t\,max}(s)\,ds\right]^{-1} \tag{9}$$

Thus, the kinetic equation (7) with the conditions (8-10) is a mathematical model for the study of subcritical growth in the corrosion-fatigue crack in the elements of vehicles' structures on symmetrical loading.

The realization of the mathematical problem (7-10) for specific cases is associated with significant mathematical difficulties. Therefore, the problem solution is simplified in analogy with [11]. Consequently, a half-space with a plane surface crack, into which the corrosive environment enters, is stretched cyclically at endlessly distant points, which are uniformly distributed by the amplitude σ and directed perpendicular to the plane of the crack placement. According to the results [11-12], the growth rate V of the crack under consideration in its straightforward propagation is related to the parameters of the stress-strain state in the prefracture area by the ratios:

$$V = f\left(K_{I\,max}\right)$$

$$f(K_{I\,max}) = \frac{\beta_1(1-R)^4(K_{I\,max}^4 - K_{scc\,max}^4) + \eta_2(K_{I\,max}^2 - K_{scc\,max}^2)}{K_{fC}^2 - K_{I\,max}^2} \tag{10}$$

Similar to the [11-12], the case, in which destruction occurs under the action of cyclic loads and a corrosive-aggressive environment in one plane of a three-dimensional body, is considered. Since the crack propagates along the normal to its periphery, the movement in the time period ΔN of the arbitrary point M of the crack periphery runs towards the normal (Figure 2).

$$MM' = \Delta N \cdot V$$

Hence, the growth in the radius vector $\Delta\rho$ of the polar system $O\,\rho\,\varphi$ (Figure 2) is written thus:

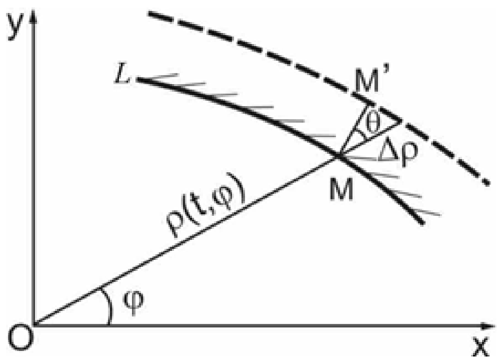

Fig. 2. Scheme for the local growth of a flat corrosion-fatigue crack [11]

$$\Delta\rho = \frac{|MM'|}{\cos\theta} = \frac{\Delta N \cdot V}{\cos\theta}, \tag{11}$$

where θ is the angle between the direction of the radius vector ρ and the normal to the crack periphery MM'. Based on the analysis of geometric construction, in Figure 2, we get [11-12]:

$$\cos\theta = \frac{\rho}{\sqrt{\rho^2 + \left(\dfrac{\partial\rho}{\partial\varphi}\right)^2}}. \tag{12}$$

Substituting 14 for 13 and moving to the boundary at $\Delta N \to 0$, the velocity is:

$$V = \frac{\partial \rho}{\partial N}\left(1 + \frac{1}{\rho^2}\left(\frac{\partial \rho}{\partial \varphi}\right)^2\right)^{-1/2}. \tag{13}$$

In addition, based on 11 and 15, to find an unknown function $\rho = \rho(N, \varphi)$, the differential equation is deduced:

$$\frac{\partial \rho}{\partial N} = f\left(K_{I\,max}\right)\left(1 + \rho^{-2}\left(\frac{\partial \rho}{\partial \varphi}\right)^2\right)^{1/2}. \tag{14}$$

At initial and final terms:

$$\begin{aligned} &N = 0, \qquad \rho(0, \varphi_0) = \rho_0; \\ &N = N_*, \qquad \rho(N_*, \varphi_*) = \rho_*. \end{aligned} \tag{15}$$

In this case, Relations 16-17 define the problem for determining the kinetics of propagation and the period N_* of subcritical growth in the surface crack under study (residual life) in the metal structure element of the vehicle. To determine ρ_*, φ_*, the condition (Irwin's criterion [4]) is added:

$$K_{I*}(\rho_*, \varphi_*) = K_{Ic}. \tag{16}$$

To realize the mathematical model (16-18), the following approximate approach [12-13] is proposed, according to which the change in the area of a moving crack of the considered configuration is approximately the same as for a semicircular crack of a radius a of a plane initial area. The rate of periphery propagation of such a crack is defined by the constant in all its points for the maximum value $K_{I\,max}$. Therefore, an error in the resulting residual life N_* occurs in increasing the value of the durability reserve, that is, 16 is simplified to:

$$\frac{da}{dN} = \frac{\beta_1(1-R)^4\,[K_{I\,max}^4(a) - K_{sccmax}^4] + \eta_2\,[K_{I\,max}^2(a) - K_{sccmax}^2]}{K_{fC}^2 - K_{I\,max}^2(a)} \tag{17}$$

At initial and final terms:

$$\begin{aligned} &N = 0, \qquad \sqrt{2\pi^{-1} S_0} = a_0; \\ &N = N_*, \qquad a(N_*) = a_*. \end{aligned} \tag{18}$$

where $K_{I\,max}$ for a half-space with a surface semicircular crack under tension is determined based on [13]:

$$K_{I\,max} = 1.17\sigma\sqrt{a} \tag{19}$$

By substituting 21 for 19 and integrating it under the relevant conditions (20), to determine the period $N = N_*$ of subcritical growth in the corrosion-fatigue crack of the initial area $S = S_0$ in the half-space, the following dependence is developed:

$$N_* = \int_{a_0}^{a_*} \frac{K_{fC}^2 - 1{,}37a\sigma^2}{\beta_1(1-R)^4[1{,}87a^2\sigma^4 - K_{scc\,max}^4] + \eta_2[1{,}37a\sigma^2 - K_{scc\,max}^2]} da \tag{20}$$

where $a_0 = \sqrt{2\pi^{-1}S_0}$, $a_* = 0{,}73K_{fC}^2\sigma^{-2}$

3. RESULTS

To study the implementation of the proposed model, the case associated with the case of individual soils [14] is considered: the development of a surface corrosion crack in a vehicle's metal structure element made of steel (17G1C), in a corrosive environment (3% solution of sodium chloride). The load frequency is assumed to be 1 Hz, which is included in the asymmetry of the cycle $R = 0{,}1$ with the loading amplitude $\sigma = 200\,МПа$. The critical size of the crack in this case is $a_* = 0{,}237\,м$, and the kinetic diagram of the corrosion-fatigue crack growth is described by the ratio [10-11]:

$$\frac{dl}{dN} \approx \frac{5\cdot10^{-6}(K_{I\,max}^2 - 25)}{12996 - K_{I\,max}^2} \tag{21}$$

Substituting the given data in 22 and integrating the sub-integral integer numerically, the value N_* is derived

$$N_* = 2\cdot10^5(a_0 - 0{,}419\,ln\,a_0 - 0{,}84) \text{ cycles} \tag{22}$$

Based on the above (Figure 3), a dependency graph of the period of subcritical growth in the corrosion-fatigue cracks on the size of the crack a_0 is developed. Consequently, as seen in Figure 3, the reduction of the crack size dramatically increases the period of subcritical growth of the crack N_*.

The residual life of the vehicle's metal structure element concerns a plate with a surface semi-elliptic crack. Let us consider the steel plate 17G1C, with the thickness h weakened by a surface semi-elliptic crack, and a_0 and b_0 ($b_o > a_o$) as the semi-axes, in which a 3% solution of sodium chloride falls (Figure 4) [14]. It is assumed that the plate is stretched at infinitely distant points perpendicular to the plane of crack propagation by evenly distributed cyclic forces of the amplitude with a 1-Hz frequency and cycle asymmetry $R = 0{,}1$. The task is to determine the number of load cycles $N = N_*$, in which the corrosion-fatigue crack periphery will become tangent to its opposite surface. Therefore, the kinetic diagram of the corrosion-fatigue crack propagation in the plate material is described by analytic dependence (23).

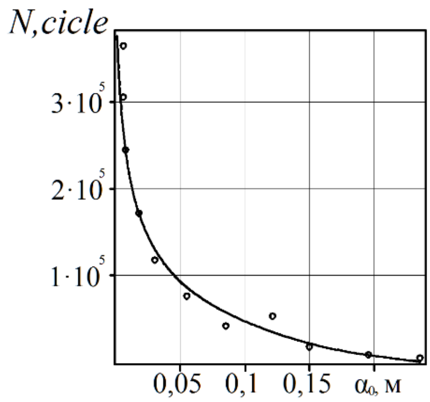

Fig. 3. Dependence of residual life N_* on the initial size of a surface crack a_0

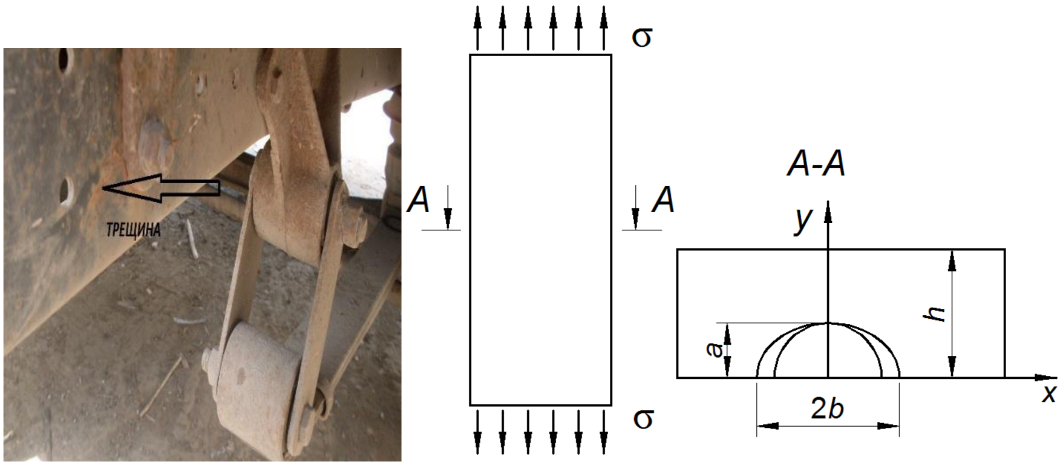

Fig. 4. Corrosion-fatigue crack of the vehicle's carrier [23] and the scheme of loading the plate with a surface semi-elliptic crack [15]

The solution is performed by the method of equivalent areas [12-13]. According to this method, the change in area, due to the corrosion-fatigue crack propagation of the considered configuration, will be approximated as for a semicircular crack with a radius a of the same initial area. The propagation velocity of its periphery points is assumed to be approximately the same. The crack periphery in a plate restricts an area, which is equal to a semi-elliptical real crack, on account of a semicircular radius a. Therefore, to replace this problem with a model, the maximum value of the SIF along this chosen circular is [13]:

$$K_I = 2\sigma\sqrt{h\pi^{-1}}F(\varepsilon), \quad F(\varepsilon) = \sqrt{\varepsilon}(1{,}01 + 0{,}067\,\varepsilon^3)(1{,}57 - 0{,}51e^{-0{,}21\varepsilon^2}), \ \varepsilon = ah^{-1}. \tag{23}$$

Substituting 25 for 23 in order to determine the period $N = N_*$, the following equation is deduced:

$$\frac{d\varepsilon}{dN} \approx \frac{5 \cdot 10^{-6} h^{-1}[4h\pi^{-1}\sigma^2 F^2(\varepsilon) - 25]}{12996 - 4h\pi^{-1}\sigma^2 F^2(\varepsilon)} \tag{24}$$

At initial and final terms:

$$N = 0,\ \varepsilon = \varepsilon_0 = h^{-1}\sqrt{a_0 b_0};\ N = N_*,\ \varepsilon = 1.$$

To determine $N = N_*$, (26) integrates within the given initial and final conditions. As a result:

$$N_* = 2 \cdot 10^5 h \int_{\varepsilon_0}^{1} \frac{[12996 - 4h\pi^{-1}\sigma^2 F^2(\varepsilon)]}{[4h\pi^{-1}\sigma^2 F^2(\varepsilon) - 25]} d\varepsilon \tag{25}$$

Numerical analysis of the expression is performed at $h = 0.04$ m, $\sigma =$ 70MPa. As a result, 27 is written as:

$$N_* = 8 \cdot 10^3 \int_{\varepsilon_0}^{1} \frac{12996 - 250F^2(\varepsilon)}{250F^2(\varepsilon) - 25} d\varepsilon \tag{26}$$

Based on 28, the dependency graph of the residual life of the plate with a surface corrosion-fatigue crack in the initial size ε_0 (Figure 5) is developed. Therefore, a small increase in the initial size ε_0 significantly reduces the period of the surface corrosion-fatigue crack growth N_* in the vehicle's metal structure.

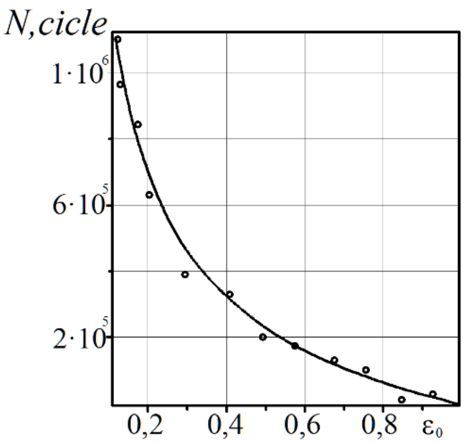

Fig. 5. Dependence of the period on N_* of a surface corrosion-fatigue crack growth in the initial size ε_0

4. CONCLUSIONS

For the case of the action of variable loads in aggressive environments on vehicles' structures with corrosive surface cracks, a mathematical model is developed: the non-linear differential equation in partial derivatives and the initial and final terms for calculating the period of subcritical growth of corrosion-fatigue cracks in these elements of vehicles. The effective method for an approximate solution of this analytic problem is substantiated. The implementation of the mathematical model is demonstrated using the example of calculating the durability of the vehicle's element as the residual life of a plate made of 17G1S steel, which is weakened by a surface semi-elliptic crack under the action of cyclic loads in a solution of sodium chloride. A slight increase in the initial sizes of corrosive surface cracks is found to significantly reduce the durability of vehicles' structural elements.

References

1. Severnyi A.Ye. 1993. *Stability and corrosion protection of agricultural machinery*. Moscow: State Research and Technological Institute.
2. Pohmurskyi V.I., M.S. Khoma. 2008. *Corrosive fatigue of metals and alloys*. Lviv: Spolom.
3. Romaniv O.N., S.Ya. Yarema, G.N. Nikiforchyn, N.A. Makhutov, M.M. Stadnyk. 1990. *Fatigue and cyclic crack resistance of structural materials*. Kiev: Naukova Dumka.
4. Cherepanov G.P. 1974. *Mechanics of brittle failure*. Moscow: Nauka.
5. Dmytrah I.M., V.V. Panasiuk. 1999. *Influence of corrosive media on local destruction of metals near stress concentrators.* Liviv: PMI NASU.
6. Korneyenko S.V., O.M. Korbutiak. 2008. „Resources of underground geological space of Ukraine". *Geology* 43: 51-53.
7. Korneyenko S., O.M. Korbutiak. 2009. „Problems of the influence of soil environment on corrosion of main gas pipelines of Ukraine". *Geology* 46: 42-43.
8. Maltseva G. N. 2000. *Corrosion and protection of equipment against corrosion.* Penza.
9. Andreykiv O.Ye., M.V. Kit. 2006. Determination of residual durability of thin-walled elements of structures at two-axis loads. *Physical-Chemical Mechanics of Materials* 1: 11-16.
10. Andreykiv O.Ye., M.V. Kit. 2006. „Determination of the period of subcritical growth of cracks in the elements of structures at their two-frequency loads". *Machine Science* 2: 3-9.
11. Andreykiv O.Ye., N.B. Sas. 2008. "The subcritical growth of a flat crack in a three-dimensional body at high temperature creep". *Physical-Chemical Mechanics of Materials* 2: 19-26.
12. Andreykiv O.Ye., A.I. Darchuk. 1992. *Fatigue failure and durability of structures.* Kiev: Naukova Dumka.
13. *Directory of stress intensity coefficients*. 1990. Mir: Murakami.
14. Tsyrulnyk O.T., D.Yu. Petryna, M.I. Hredil. 2006. "The fracture peculiarities of trunk pipeline steels after their long term service". *Proceedings of the international conference on Crack paths (CP 2006)*. Paper No 61. Parma, Italy, 14th-16th September 2006.

15. Shchurin K.V. 1994. *Forecasting and increasing the fatigue life of the bearing systems of agricultural tractor means.* Dissertation of Doctor of Science (Engineering). Orenburg.
16. Figlus T. 2015. The application of a continuous wavelet transform for diagnosing damage to the timing chain tensioner in a motorcycle engine. *Journal of Vibroengineering*17(3): 1286-1294. ISSN: 1392-8716.
17. Koziol M., T. Figlus. 2017. Evaluation of the failure progress in the static bending of GFRP laminates reinforced with a classic plain-woven fabric and a 3d fabric, by means of the vibrations analysis. *Polymer Composites* 38(6): 1070-1085. DOI: 10.1002/pc.23670.
18. *Ukrayina u tsyfrakh. Statystychnyy zbirnyk*. Vidpovidal'nyy za vypusk O.A. Vyshnevs'ka. Za redaktsiyeyu: I.Ye. 2017. Vernera. Kyyiv: Derzhavna sluzhba statystyky Ukrayiny. [In Ukrainian: *Ukraine on numbers. Static zbirnik*. Edited by I.E. Werner. Kiyiv: State Statistics Service].
19. Kosicka E., E. Kozłowski, D. Mazurkiewicz. 2015. „The use of stationary tests for analysis of monitored residual processes". *Eksploatacja i Niezawodnosc – Maintenance and Reliability* 17(4): 604-609. DOI: http://dx.doi.org/10.17531/ein.2015.4.17.
20. Maruschak Pavlo, Sergey Panin, Ilya Vlasov, Olegas Prentkovskis, Iryna Danyliuk. 2015. „Structural levels of the nucleation and growth of fatigue crack in 17Mn1Si steel pipeline after long-term service". *Transport* 30(1): 15-23.
21. Maruschak P., Poberezhny L., Pyrig T. 2013. "Fatigue and brittle fracture of carbon steel of gas and oil pipelines". *Transport* 28(3): 270-275.
22. Figlus Tomasz, Marcin Stańczyk. 2014. "Diagnosis of the wear of gears in the gearbox using the wavelet packet transform". *Metalurgija* 53(4): 673-676. ISSN: 0543-5846.

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