Prediction of cracks growth in the main pipeline based on the elastoplastic model

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Abstract. A method is proposed for predicting the growth of surface cracks in the wall of a main pipeline under the action of exploitative forces. An elastoplastic model for the growth of surface cracks under biaxial loading is described using steel 20 as an example. Using the ANSYS program, a crack growth modeling algorithm has been developed which takes into account residual stresses. The forms and magnitudes of crack opening for variable cycles of pipeline loading are determined. The influence of the stress state before the crack tip at variable loads on the growth rate of cracks has been established. The effect of overload cycles on crack growth is researched. A method for predicting the development of cracks according to the internal diagnostics of the pipeline and monitoring their loading is described.

1. Introduction

The most important factor in maintaining the operability and reliability of the main pipeline is to assess the possibility of an emergency or failure caused by fatigue fracture due to changing pressure cycles The degree of exposure of the pipeline to fatigue failure depends on the mechanical characteristics of the steel, the pipe manufacturing technology, the loading history and the value of the internal pressure. To assess the susceptibility of a fatigue failure pipeline, a methodology for identifying cracks is selected, such as hydrostatic testing or linear internal diagnostics of pipeline using physical methods of non-destructive testing. The selected methodology for on-line monitoring of the main pipeline should confirm that the pipeline is operating in safe mode. This is usually achieved by assessing the growth of fatigue cracks, and then by re-checking the pipeline in the time period selected to minimize the crash risk from the growth of fatigue cracks, as well as to minimize the price of diagnostics [1].

In order to avoid accidents on the main pipeline, it is necessary to more accurately predict the growth of detected cracks and, accordingly, estimate the residual life of the pipeline. Correctly predicted growth of cracks after internal pipe diagnostics allows optimizing the technological mode of pumping oil or gas and reducing the cost of current and major repairs of pipelines [2].

The cracks of normal failure type originate and grow in the plane perpendicular to the greatest principal stresses. In the pipeline wall, such stresses are the circular stresses arising from the internal pressure in the process of pumping oil or gas through it. The results of internal pipe diagnostics and the analysis of emergency situations confirm that the most dangerous are surface cracks developing in the axial plane of the pipe. It is believed that the destruction of the pipeline occurs when a crack grows through the entire thickness of the pipe wall [3].

In the process of pumping oil through the main pipeline, engineering services responsible for troubleproof operation to assess the risk of defects of various origins in the pipe wall use formulas for the growth rate of cracks, usually created on the theoretical basis of fracture mechanics. The formulas for the growth rate of cracks reflect their physical growth models, which take into account the mechanical characteristics of the pipe wall material, the type of loading, the biaxial type of stresses and the variable cyclical pressure during exploitation of the pipeline [1].

Currently, computer programs are used to calculate the residual life of pipelines, which allow interactively assess the growth of the most dangerous cracks found during diagnostics by non-destructive control methods [4].

Actual are studies of the fatigue cracks growth from the standpoint of fracture mechanics, taking into account the effects associated with the development of plastic deformation with increasing crack sizes during each loading cycle. These effects primarily include residual stresses, crack closure, growth rate retardation, and the interaction of variable load cycles [5, 6]. In experimental researches [7, 8], the interaction of constant and changing load cycles on the growth rate of fatigue cracks in steel and nickel samples was studied. In these researches, the phenomenon of crack closure was studied, and it was found that the elastic fracture mechanics does not allow modelling effects accompanied by large plastic deformations at the crack tip.

The proposed study describes a method for predicting the growth of surface cracks in the steel wall of main pipeline with constant and variable loading cycles, taking into account the biaxial stress state.

2. Theory

For main pipelines, the most dangerous defects of the pipe wall are longitudinal cracks, which are recorded by diagnostic projectiles moving together with the product being transported (Fig. 1a). In the course of diagnostics, the exact location of the defect is established, its size and shape, after which a calculated scheme is drawn up, on which the detected defects are most often modeled as the semi-elliptical cracks [9].

When transporting through the main pipeline of the product under pressure, a biaxial stress state occurs in its wall (Fig. 1b). In longitudinal axial sections of the pipe, circular stresses occur, which are maximum stresses and depend on the diameter of the pipe, wall thickness and working pressure in the pipeline, so they are always tensile, i.e. positive. The cracks of normal separation most often arise on the surface of the pipe and develop in a plane perpendicular to the circular stresses.

Axial stresses σ_{ax} occur in the cross sections of the pipeline. They vary with temperature in the pipe, and depending on the direction of bending, they can be both tensile and compressive [10].

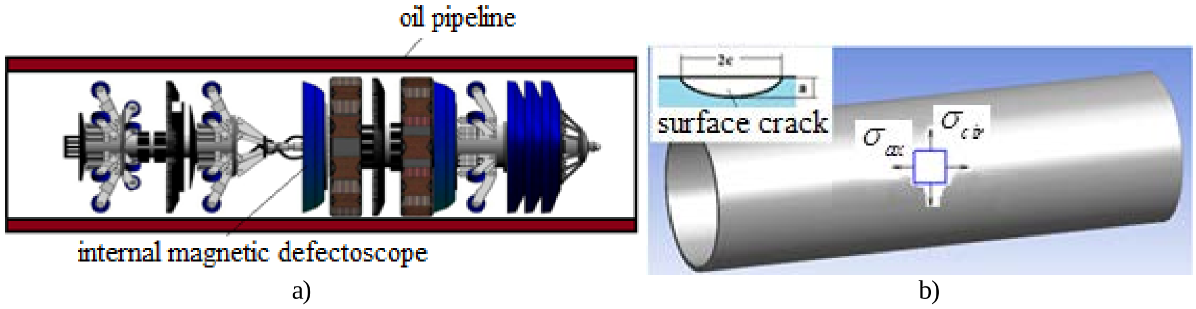


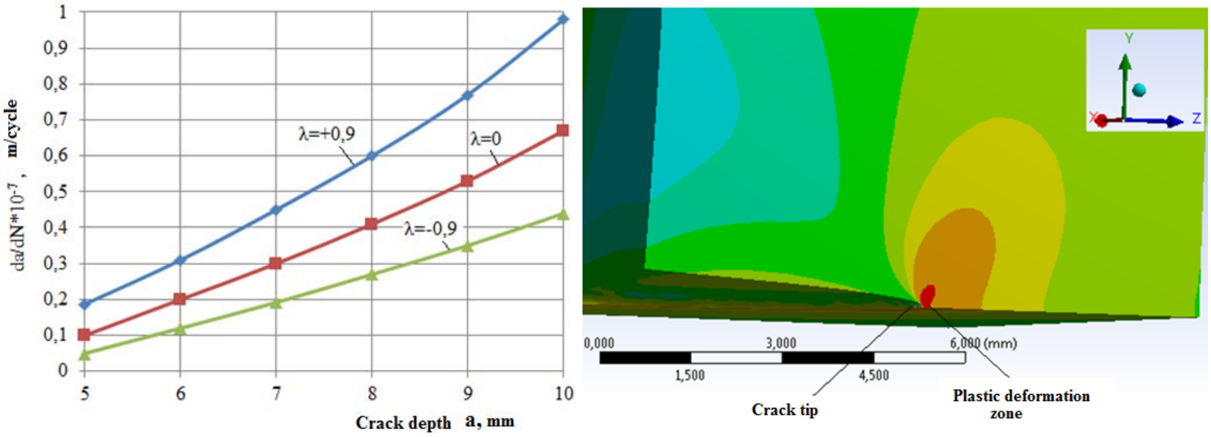
Figure 1. The main pipeline: a) - internal magnetic defectoscope; b) - stress state in the pipe wall

In the articles [11], [12], the dependence of the growth rate of fatigue cracks on the type of stress state ahead of the fatigue crack front was obtained by comparing the experimental data and computational data made by the finite element method in the elastoplastic formulation of the problem. It is established that the growth rate of fatigue cracks depends on the size, shape and value of plastic deformations at the crack tip. The article [13] describes an approach to calculating the growth rate of fatigue cracks, taking into account both the stage of loading of a surface crack and the stage of its unloading. The formula for the growth rate of fatigue cracks is obtained depending on the magnitude of the average stresses in the embrittlement zone at the crack tip.

In the described study, a pipeline made of steel 20 was modeled. A series of tests was carried out [9], in which the growth rate of surface cracks was experimentally determined for various types of biaxial loading (Fig. 2).

As follows from Fig. 2a, the fastest fatigue crack growth rate was recorded for a more brittle state of steel under biaxial tension (degree of loading biaxiality $\lambda = +0,9$), and the smallest rate was recorded for a more ductile state under biaxial tension-compression (degree of loading biaxiality $\lambda = -0,9$).

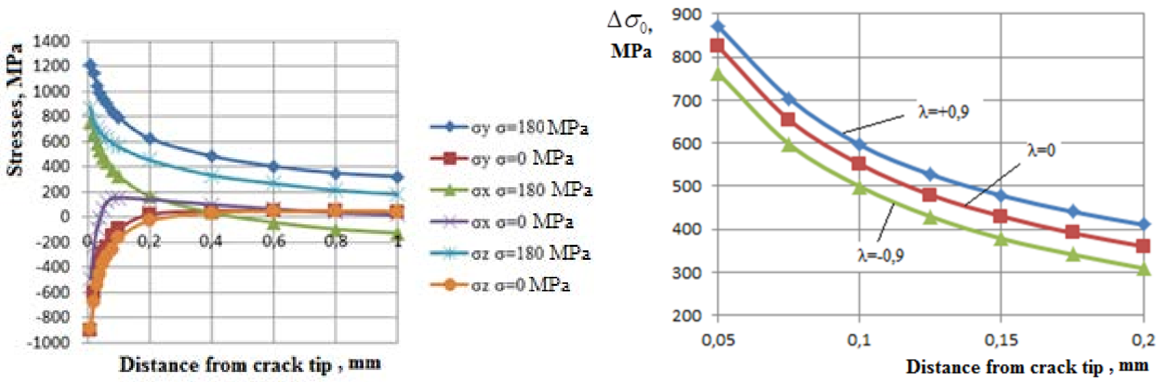
Surface cracks were modeled by the finite element method in the ANSYS Workbench program (Fig. 2b). In the elastoplastic formulation of the problem, the stresses at the crack tip during the loading cycle of the model and unloading to zero were determined.



a) b)

Figure 2. The results of steel 20 tests: a) growth rate diagrams for various types of loading; b) surface crack model

For all types of loading, it was determined that at maximum load of solid with a surface crack , all stresses ahead the crack front have high positive values, i.e. metal is in a state of triaxial tension. When unloading solid with crack to zero, all stresses at the crack tip change their sign to the opposite and have high negative values, i.e. the metal goes into the state of triaxial compression (Fig. 3a). Such effects are explained by the development of plastic deformations at the crack tip in the direction normal to the crack growth plane during loading and the occurrence of residual deformations when the body with a crack is unloaded [13].



a) b)

Figure 3. Determination of the normal stresses at the crack tip for steel 20: a) stresses under load and unload; b) the difference of average stresses per cycle

For fatigue cracks of normal opening, it is assumed that their growth rate under various types of loading depends on the magnitude of average stresses developing ahead the crack front.

$$\sigma_0 = \frac{\sigma_x + \sigma_y + \sigma_z}{3}. \qquad (1)$$

The sum of the normal stresses is the invariant of the stress state at the point in question and, accordingly, can be written in the principal stresses, and the crack growth plane will be oriented normally to the largest principal stress σ_1.

When comparing the crack growth rate for various types of loading, determined experimentally, with the values of normal stresses ahead of the crack front, calculated by the finite element method

(Fig. 3a), the dependence of the crack rate on the difference of average stresses during the loading cycle from the maximum load $\sigma_0^{(+)}$ to the maximum unloading $\sigma_0^{(-)}$ (Fig. 3b)

$$\Delta\sigma_0 = \sigma_0^{(+)} - \sigma_0^{(-)} . \tag{2}$$

Figure 3b shows the distribution of the difference of average stress at the crack tip for maximum load and unloading to zero. By analogy with the stress intensity factor K_I , the average stress intensity can be described with the help of the average stress change factor per loading cycle $\Delta K_{\sigma 0}$

$$\Delta K_{\sigma 0} = \Delta\sigma_0 \sqrt{2\pi r} , \tag{3}$$

where r – the distance from the crack tip to the point at which the difference of average stresses is calculated (Fig. 3b).

The formula for the growth rate of fatigue cracks for an elastoplastic model in common will take the following form

$$\frac{da}{dN} = C_1 \left(\Delta K_{\sigma 0}\right)^{n_1} , \tag{4}$$

where C_1 and n_1 – material characteristics; a – crack size; N – the number of loading cycles.

The constants C_1 and n_1 of the material differ from the constants C and n in the Paris formula, which is most often used for practical calculations, but they can be determined from any fatigue tests for which you can construct a kinetic diagram and perform an elastoplastic model of a crack in a loaded body or specimen.

In the proposed research, according to the data of the above experiments, a formula was obtained for the growth rate of fatigue cracks in steel 20

$$\frac{da}{dN} = 1{,}38 \cdot 10^{-11} \left(\Delta K_{\sigma 0}\right)^{2.9} . \tag{5}$$

Using this formula, it is possible to calculate the residual life of a pipeline with a crack during stable loading cycles

$$N_{rl} = \int_{a_{reg}}^{a_{cr}} \frac{1}{1{,}38 \cdot 10^{-11} \left(\Delta K_{\sigma 0}\right)^{2{,}9}} da , \tag{6}$$

where N_{rl} – the residual life or the number of loading cycles to the critical size of the crack; a_{reg} – the size of the crack at the time of its registration; a_{cr} – critical crack size.

For a main pipeline, the critical size of a crack can be determined when it full grows through the wall or is specified by regulatory documents.

The operability of pipes in pipelines is significantly affected by cyclic loads – loading cycles with internal pressure [14]. The loading cycles presented in Figure 4 are, as a rule, caused by various production factors: changes in the technological modes of operation with changes in daily transportation volumes; technological switching during repair and preparatory work; uneven filling of tanks in the tank farms of the head pumping stations and so on.

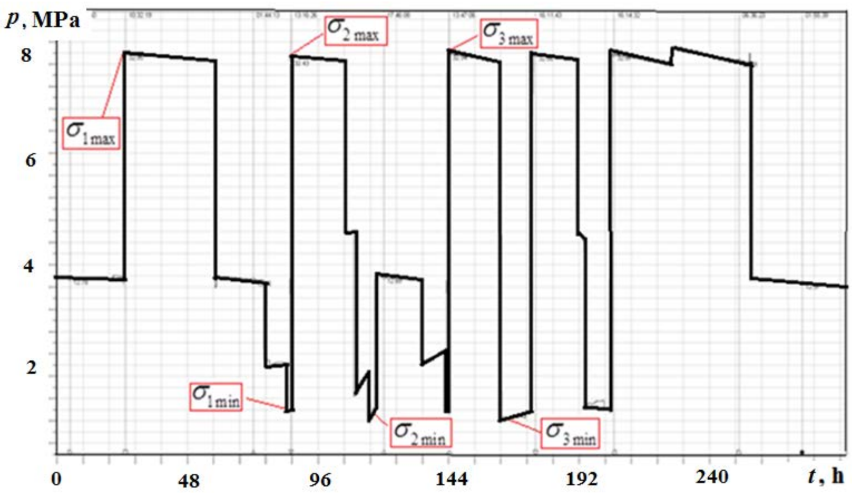


Figure 4. Graphic representation of the pressure change on the linear section of the main pipeline in 10 days

In the conditions of non-stop pumping oil pipelines operate in conditions of rigid regimes. Under the rigidity of the operation mode of the main pipeline is understood as the frequency of changes in the internal pressure in the oil pipeline during operation. The rigidity of the operating mode can be characterized by the ratio of the number of change cycles in the internal pressure in the period under consideration to the critical number of change cycles in the internal pressure, upon reaching which fracture of the pipeline may occur.

In connection with the constantly changing conjuncture of the international hydrocarbon raw materials market and, as a result, the reorientation of cargo flows, the prediction of the fluctuations frequency of internal pressure is a problematic task. And the task of determining the growth rate of fatigue cracks in the interdiagnostic period on the basis of the recorded data on pipeline operating loads at the site of the crack is a promising and very important area of monitoring the performance of pipeline networks.

The formula of crack growth rate (5) allows taking into account the effect of large plastic deformations at the crack tip on the crack growth rate under various types of load. This effect is explained by the formation of a residual deformations field, which, in turn, changes the deformation pattern of opening and closing the crack. After crack unloading, the magnitude of compressive residual stresses that occur ahead of the crack front depends on the size of the plastic deformation zone and the value of plastic stresses (Fig. 2b).

Thus, the proposed method for predicting the growth of fatigue crack size makes it possible to take into account each loading cycle under pipeline operating conditions, dividing the pressure diagram in a pipeline into loading and unloading steps (Fig. 4). In this case, the program for calculating the crack front growth can take into account the biaxial stress state in the pipeline wall, the programmed method to set the pressures, as well as such specific loading cycles as overloads, etc.

3. Results of calculation

In the proposed work, a surface longitudinal crack in the wall of the main pipeline is considered. The intention of the study is to assess the impact of changes in pressure cycles in the pipeline on the change in crack growth rate. The crack modeling and stress-strain state calculations are performed using the finite element method in the ANSYS Workbench program. Pipe material – steel 20: yield strength σ_y = 280 MPa; tensile strength σ_u = 430 MPa; relative residual elongation at break δ = 30%.

Figure 5a shows the finite element mesh for modeling the crack front 1, 2, 3 and the crack tip 4. Figure 5b shows the process of modeling three loading cycles in the ANSYS Workbench program.

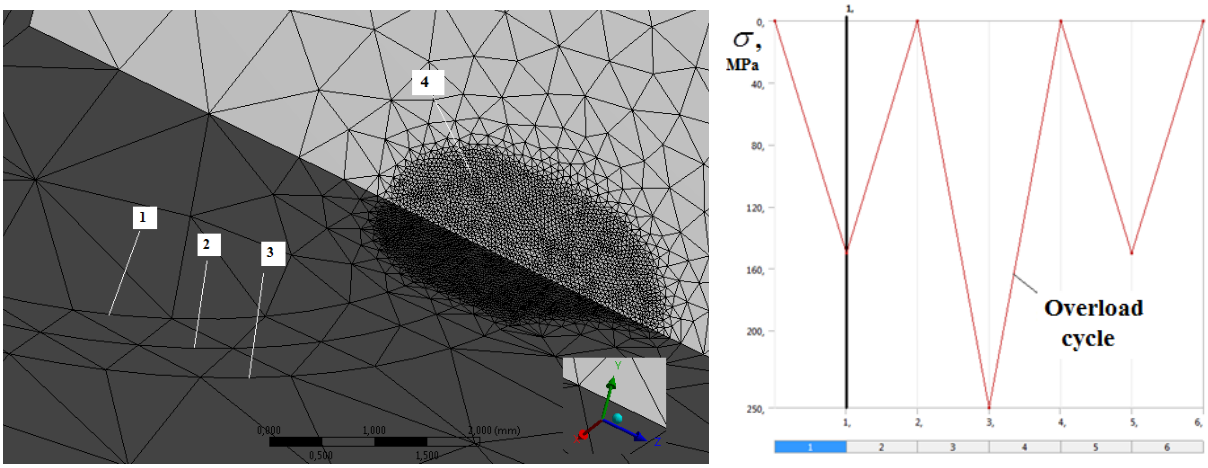


Figure 5. Modeling of surface crack: a) finite element mesh: 1, 2, 3 - three fronts of crack growth, 4 - finite element mesh at the crack tip; b) three cycles of loading, MPa

The variant of loading the pipe in three cycles, which create circular stresses in the pipe wall, is considered: 1st cycle 150 MPa; 2nd cycle 150, 200 and 250 MPa; 3rd cycle 150 MPa. Each cycle during unloading is reduced to a stress equal 0 MPa. The first and third loading cycles characterize the stable operation of the pipeline, and the second cycle is an overload cycle. Under such loading, after the overload cycle, the crack growth rate decreases, as described in articles [15, 16]. It is required to determine the ability of the elastoplastic model described above and formula (5) to reflect the phenomenon of decreasing crack growth rate after an overload cycle.

For simplicity of modeling, a semicircular surface crack with a conditional depth is considered: 1st cycle – 5 mm; 2nd cycle – 5.5 mm; 3rd cycle – 6 mm. In the ANSYS Workbench program, three variants of crack growth were modeled, with each load variant changing only the value of the second loading cycle: 150, 200 and 250 MPa. Since a semicircular crack has two planes of symmetry, when modeling it using the finite element method, only a fourth part of the pipe element with crack was considered.

To compare the variants of loading a stable crack (without an overload cycle) and crack with an overload cycle, the crack opening magnitude was calculated – the displacement of the crack faces perpendicular to its growth plane (Fig. 6 and 7) and normal stresses ahead of the crack front at a distance of 0.05 mm from its top (Fig.8 and 9).

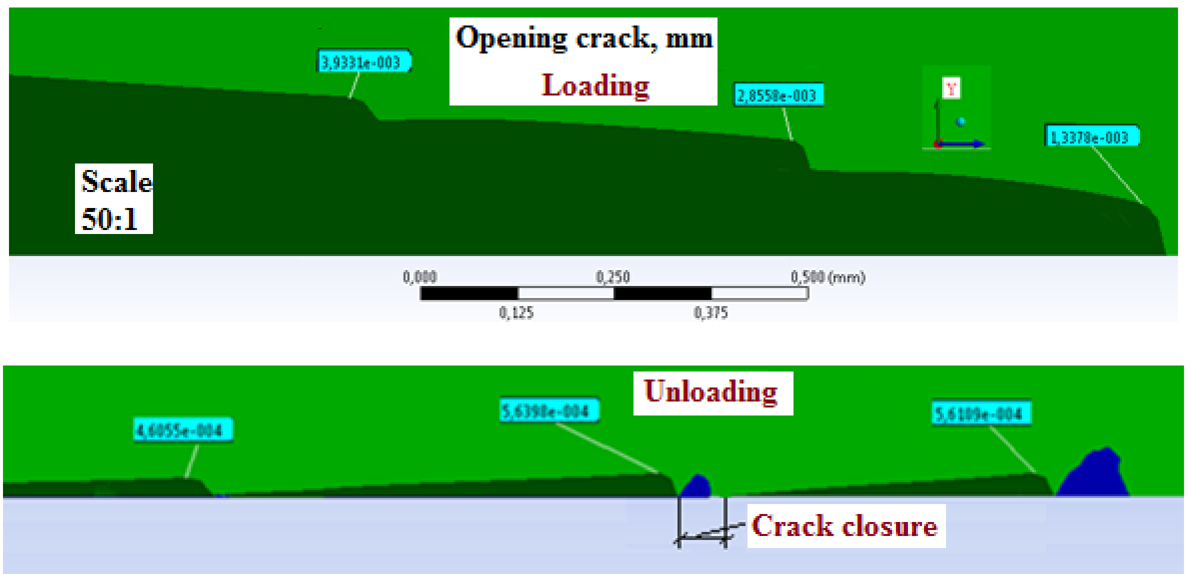


Figure 6. Opening of crack. Stable cycle $\sigma_{cr} = 150\ MPa$.

Study of the movement of the crack surfaces or the crack opening makes it possible to present a physical phenomena picture occurring at the crack tip. Stable cycles of loading and unloading cracks are characterized by a steady increase in crack opening (Fig. 6). In the course of calculations, taking account of plastic deformations makes it possible to see on the crack surface the traces of the crack front during each loading cycle. Due to the concentration of the plastic deformation zone at the crack tip in the direction perpendicular to the crack plane, during crack unloading residual deformations create compressive stresses ahead the crack and create conditions for closing the crack according to Elber [17]. At the same time, near to the top, the crack remains open and the opposite surfaces of the crack do not close.

It was determined that the overload cycle (Fig. 7) increased the crack opening compared with stable cyclic loading at the load stage - from $2.8 \cdot 10^{-3}$ to $6.9\ 10^{-3}$ mm, and at the unloading stage – from $5.6\ 10^{-4}$ to $5.0 \cdot 10^{-3}$ mm. On the cycle following the overload, on the contrary, the crack opening decreased compared to a stable cyclic loading at the loading stage from $13.0 \cdot 10^{-4}$ to $6.8 \cdot 10^{-4}$ mm, and at the unloading stage from $6.8 \cdot 10^{-4}$ to $1.9 \cdot 10^{-4}$ mm.

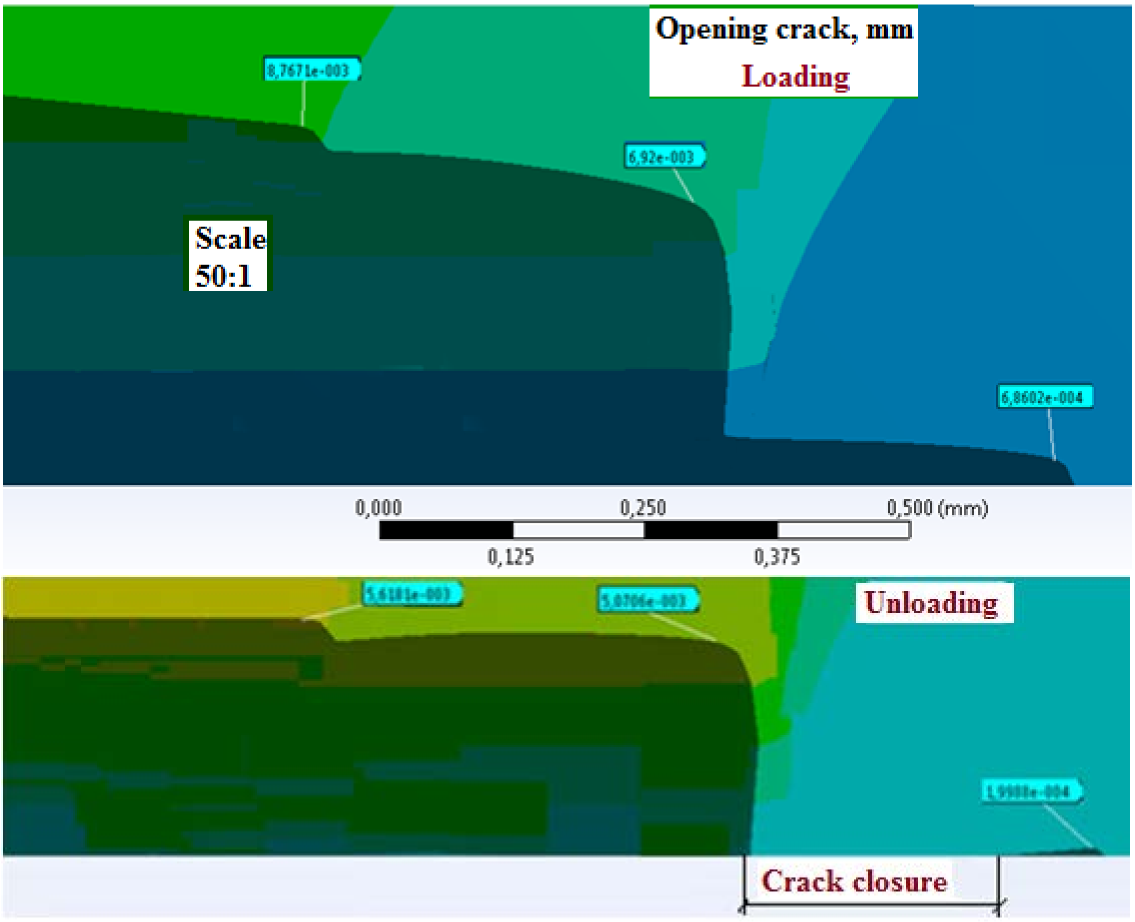


Figure 7. Opening of crack. Overload cycle $\sigma_{cr} = 250\ MPa$.

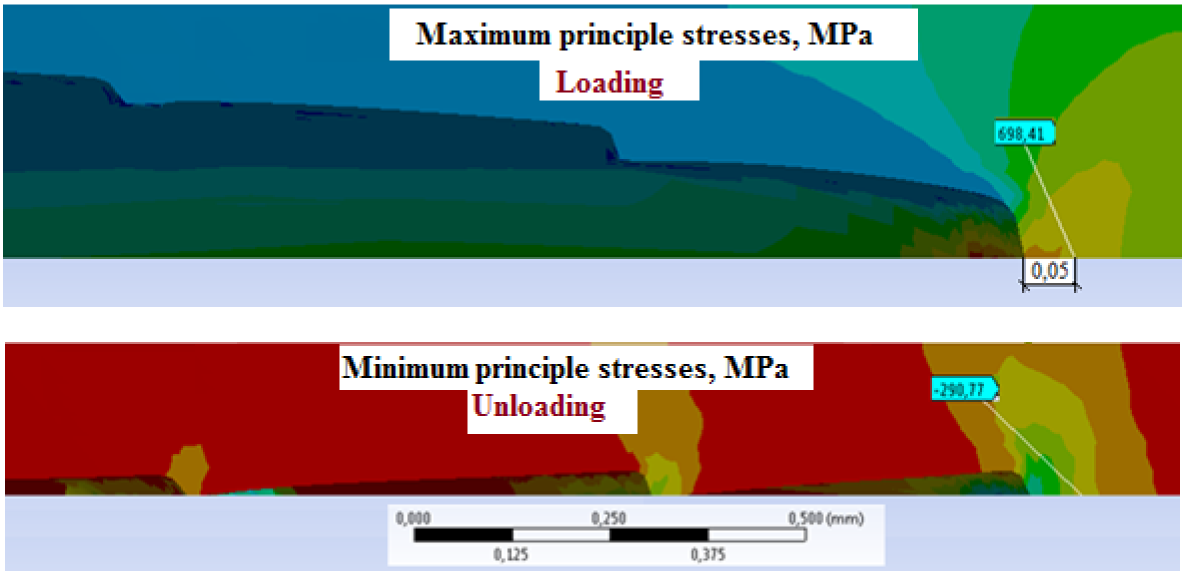


Figure 8. Normal stresses ahead of the crack front. Stable cycle $\sigma_{cr} = 150\ MPa$.

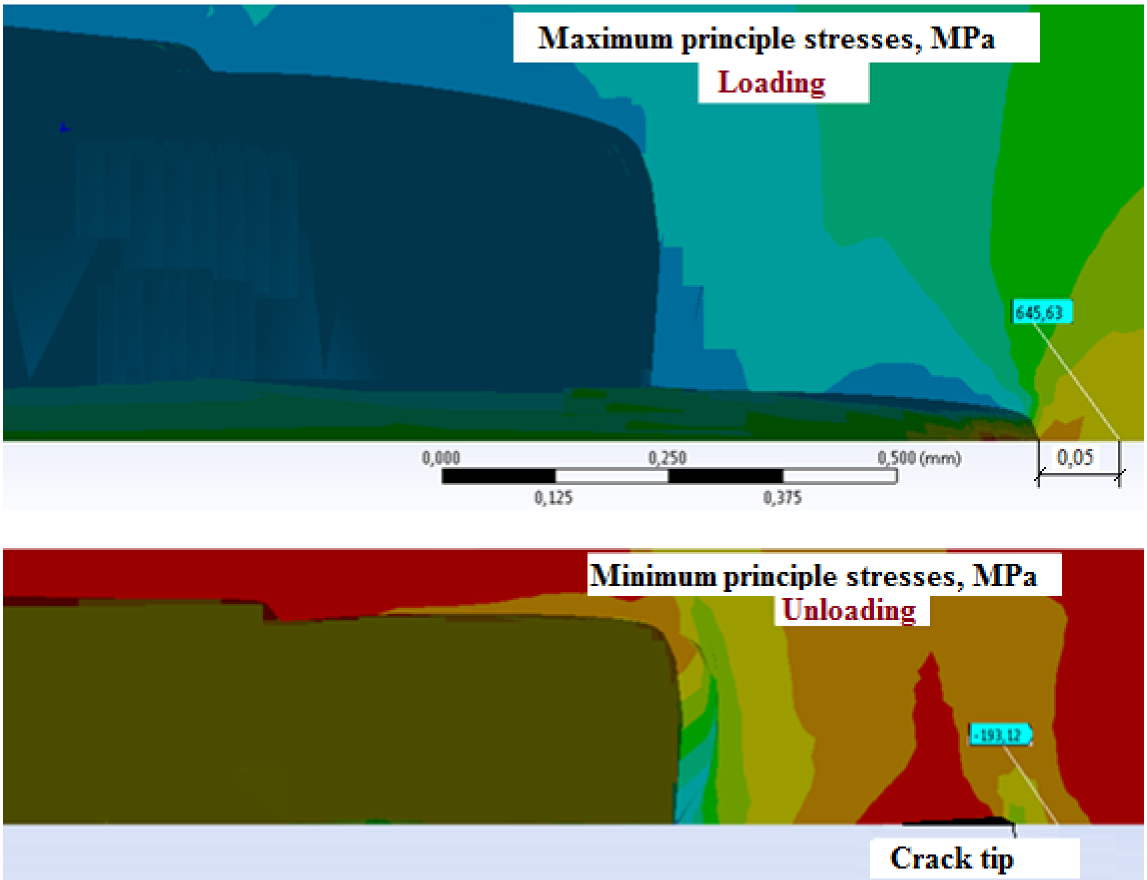


Figure 9. Normal stresses ahead of the crack front. Overload cycle $\sigma_{cr} = 250\ MPa$.

Figures 6 and 7 show that after unloading the crack in the case of a stable cycle, the crack closure is much less than in the case of the overload cycle, i.e. the greater the closure of the crack, the lower its speed. Thus, it is possible to indirectly determine the relationship between the crack growth rate and deformation processes, depending on the magnitude of plastic and residual deformations.

In order to calculate the crack growth rate after overload cycles, it is proposed to use an elastoplastic model, which describes the crack growth rate by equation (5). Stresses were determined at a distance of 0.05 mm ahead of the crack front after three conditional cycles of loading (Fig. 8 and Fig. 9). Table 1 shows the results of the calculation of the principles stresses σ_1, σ_2, σ_3 for the three variants of cyclic crack loading: stable cycle $\sigma = 150$ MPa; two cycles with overload $\sigma = 200$ MPa, $\sigma = 250$ MPa.

Table 1. The results of calculating the growth rate of cracks for different loading cycles

Overload cycle, MPa	Principal stresses, MPa						σ_0, MPa		$\Delta\sigma_0$ MPa	ΔK_{σ_0} MPa·m$^{0.5}$	$\frac{da}{dN}$ m/cycle
	σ_1		σ_2		σ_3						
	a*	b*	a	b	a	b	a	b			
150 (0)	698	-54	447	-231	364	-290	503	-191	694	12,4	$0{,}21\cdot10^{-7}$
200 (50)	691	-6	431	-130	357	-209	493	-115	608	10,8	$0{,}15\cdot10^{-7}$
250 (100)	645	20	397	-94	334	-193	458	-89	547	9,7	$0{,}10\cdot10^{-7}$

* a – crack loading; b – crack unloading

The difference of average stresses (2) for the cycle following the overload cycle turned out to be the greatest for the variant of stable loading, i.e. without overload cycle, and the lowest for the variant with the highest overload. In table the values of the change coefficient of average stresses per loading cycle $\Delta K_{\sigma 0}$ (3) correspond to the values of the difference of average stresses. After substituting $\Delta K_{\sigma 0}$ into formula (5), the crack growth rate is determined. In accordance with the proposed elastoplastic model of fatigue crack growth after overload cycles, the crack growth rate decreases: for stable crack growth, the crack growth rate da/dN =0.21·10^{-7} m/cycle; for the $\sigma = 200$ MPa overload cycle, the crack growth rate da/dN = 0.15·10^{-7} m/cycle; and for the $\sigma = 250$ MPa overload cycle, the crack growth rate da/dN = 0.10·10^{-7} m/cycle. The results of the performed studies allow us to conclude that with an increase in the overload cycle stresses, the crack growth rate decreases. This conclusion is consistent with the results of the studies described in articles [16, 18].

4. Conclusion

The described elastic-plastic model for the growth of fatigue cracks makes it possible to predict the development of cracks in pipelines detected by the internal magnetic defectoscope. Using equation (4), it is possible to estimate the residual resource of the pipeline for the case of varying loading cycles. In this equation, the characteristics of material C_1 and n_1 must be known in advance or determined as a result of uniaxial fatigue testing of specimens with a crack. With known circular and axial stresses, a pipeline zone with a surface crack is modeled; the shape and dimensions of crack are determined by non-destructive testing methods. At the crack tip, the stress state is investigated and the coefficient of change of average stresses is determined for each loading cycle, taking into account residual deformations obtained in previous loading cycles. The integral equation (6) allows one to successively sum up the results of calculations for fixed load cycles.

Thus, the described method for determining the crack growth rate using formula (4) allows us to predict the size of a surface crack, if pipeline loading cycles are fixed during operation. Taking into account this information, the employees of the operational services can set the time next of internal diagnostics of pipeline and assess the residual resource of the main pipeline.

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