Determination of the residual life of the pipe metal under conditions of corrosion fatigue

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Abstract. This paper presents a method for calculating the residual metal life of pipelines with crack-like defects. The results of corrosion and fatigue tests of ordinary grade structural steel VSt3sp, widely used in the oil and gas industry, are presented. The work carried out studies on the effect of cathodic polarization on the cyclic crack resistance of VSt3sp steel under the influence of a carbonate-bicarbonate medium.

1 Introduction

Low-cycle corrosion fatigue is one of the most dangerous types of corrosion and mechanical destruction of oil trunk pipelines. Cyclic loads in the pipe arise as a result of changes in the internal pressure and temperature of the pumped product, pumping modes, and beats of the transported liquid against the walls of the pipeline. It should be noted that the vast majority of damage to main pipelines transporting, first of all, liquid hydrocarbons is associated with low-cycle corrosion fatigue, which leads to the appearance and development of corrosion-fatigue cracks in stress concentrators [1-3].

During the operation of oil trunk pipelines, defects develop on their surface in which stresses can exceed the yield strength for this material. It has been calculated that for real defects present on the surface of pipelines, such as mechanical risks, scratches, cuts, scuffles, corrosion ulcers, depending on their geometric dimensions, the theoretical stress concentration coefficient can reach 3.9 [4-7].

Consequently, the defect area under the influence of pressure of the pumped petroleum product undergoes plastic deformations that are irreversible during unloading. The safety of pipeline operation depends on many factors: the geometric parameters of the defect, the properties of the pipe metal, the presence of welds, the composition and properties of the corrosive environment [8]. When assessing the residual life of the equipment (uptime), it is necessary to take into account the geometry of defects, equipment and its operating conditions as much as possible.

According to regulatory documents, with all methods of laying pipelines, with the exception of aboveground, it is necessary to provide comprehensive corrosion protection using protective coatings and electrochemical protection methods, regardless of the aggressiveness of the soil. To correctly assess the life of metal structures under the

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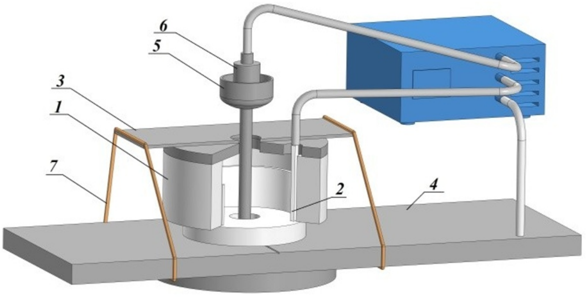
influence of cyclic loads, it is necessary to know the kinetics of fatigue crack development in these operating conditions of the equipment [9-11].

2 Methods and Materials

In order to determine the cyclic crack resistance of structural steel of ordinary quality VSt3sp, corrosion and fatigue tests were carried out in a carbonate-bicarbonate medium (1h.$NaHCO_3$+1h.Na_2CO_3). Rectangular samples made of VSt3sp steel with dimensions of 480x40x10mm with a V-shaped incision 1 mm deep, which simulated the existing stress concentrators on a real pipeline, were used as the objects under study. To assess the effect of cathodic polarization on the stability of the pipeline material to cyclic loads, tests were carried out in the same environment with the imposition of cathodic polarization in the field of protective potentials. The value of the protective potential was minus 0.7V relative to the saturated calomel reference electrode [12].

Taking into account the specifics of the operation of main oil pipelines, rigid loading of samples according to the pure bending scheme with a zero cycle was chosen to reproduce the fracture of the operational type in the samples. The deformation amplitude is 0.23%, simulating an elastic-plastic zone in stress concentrators. The loading frequency is 50 cycles/min. The application of mechanical loads with simultaneous exposure to corrosive media was accompanied by cathodic polarization of the samples during the entire time of the experiment (Figure 1).



1 – housing, 2 – auxiliary electrode made of stainless steel, 3 – bracket, 4 – sample, 5 – glass, 6 – saturated calomel reference electrode, 7 – rubber rings

Fig. 1. The scheme of the experimental installation.

The choice of a carbonate-bicarbonate medium is due to the fact that during the operation of cathodic protection stations, a layer of cathodic deposits is formed, which consists of carbonic acid salts [13].

As a result of cathodic protection in the places of destruction of the protective film, the process of alkalinization of ground electrolytes occurs according to the following reactions:

$$H_2O \xrightarrow{I_{к.з.}} 2H^+ + OH^-, \tag{1}$$

$$CO_2 + OH^- \leftrightarrow HCO_3^-, \tag{2}$$

$$HCO_3^- + OH^- \leftrightarrow CO_3^- + H_2O. \tag{3}$$

When exposed to cathodic protection currents on the surface of the pipeline in areas where the anticorrosive insulation is broken, the chemical interaction of carbon dioxide with hydroxyl ions occurs, resulting in the formation of carbonic acid salts, including carbonates and bicarbonates (formulas 1-3).

The level of carbon dioxide on the metal surface remains high due to the location of the pipeline in the soil containing carbon dioxide and the possible presence of carbonic acid salts in ground electrolytes. When carbonate-bicarbonate ions interact with cations of alkaline and alkaline-earth metals contained in soils, corresponding salts of these metals are formed on the surface of the underground pipeline, which create cathode deposits on it. Carbonates and bicarbonates react with cations of alkaline and alkaline earth metals present in the soil, forming salts of these metals on the surface of the underground pipeline, which form cathode deposits [14-16].

As a result of these processes, an alkaline medium with pH = 12 is formed on the surface of the pipe in places where insulation is missing or broken, as well as in cracks. Carbonates and bicarbonates can protect steel in the presence of oxygen. However, if the insulation coating on the pipeline surface is broken, this can lead to an increase in local corrosion.

As a result of fatigue tests, it was found that the fracture zone of the pipeline samples is 40-50% of the fracture area (Figure 2).

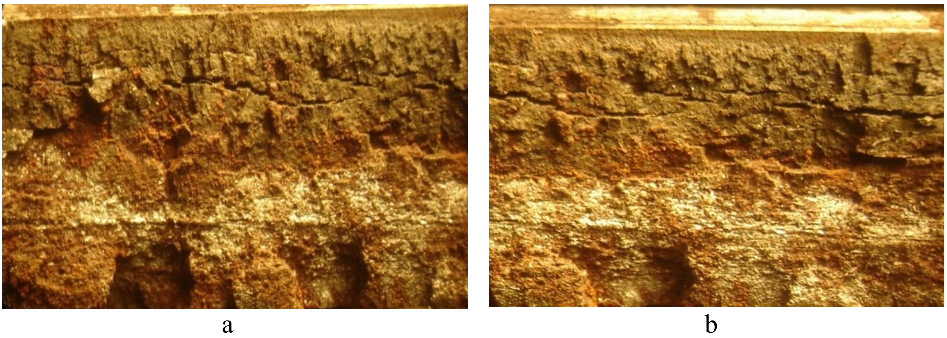


Fig. 2. Fatigue fracture: a – in a carbonate-bicarbonate medium; b – in a carbonate-bicarbonate medium with a polarization of minus 0.7V relative to a saturated calomel reference electrode.

Fatigue fractures are characterized by the presence of different zones that differ from each other. Fractures in corrosive environments have a characteristic appearance of brittle multi-layered fracture, which indicates the development of a crack from a variety of sources of damage. White cathode deposits are observed on the surface of the fractures that have been in contact with the carbonate-bicarbonate medium.

The average number of cycles before the crack origin and destruction of the sample under the influence of corrosive media and polarization are shown in Table 1.

Table 1. The number of cycles before the crack origin and destruction of the sample.

Number of cycles, N	**In a carbonate-bicarbonate medium without polarization**	**In a carbonate-bicarbonate medium with a polarization of minus 0.7 V relative to a saturated calomel reference electrode**
before the crack originates	1250	1000
before the sample collapses	6450	5050

3 Results and Discussion

Based on the results of fatigue tests, graphs of the dependence of the crack depth L on the number of loading cycles N are constructed (Figure 2).

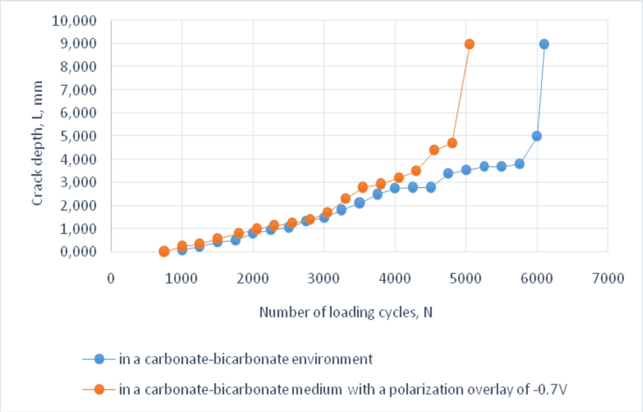


Fig. 3. Dependence of the crack depth on the number of loading cycles.

The result of any experiment is the statistical processing of experimental data. For the obtained curves (Figure 2), mathematical models of crack depth were determined using the least squares method as a function of the number of loading cycles at the stage of stable crack growth for various test conditions. The highest correlation coefficients (r=0.99) showed exponential dependencies:

1) in a carbonate-bicarbonate medium:

$$L = e^{6\cdot 10^{-4}(N-13514)}, \tag{4}$$

2) in a carbonate-bicarbonate medium with superimposed polarization:

$$L = e^{6\cdot 10^{-4}(N-13713)}. \tag{5}$$

According to the obtained dependencies (formulas 4, 5), the values of crack growth per one loading cycle are determined, reflecting the rate of crack growth. In the area of stable crack growth, the parabolic relationship between the increment of crack length during one loading cycle and the stress intensity coefficient showed the highest correlation coefficient (r=0.99):

1) in a carbonate-bicarbonate medium:

$$\frac{dL}{dN} = -14.8 \cdot 10^{-7} + 5.4 \cdot 10^{-7} \cdot \sqrt{K}, \tag{6}$$

2) in a carbonate-bicarbonate medium with superimposed polarization:

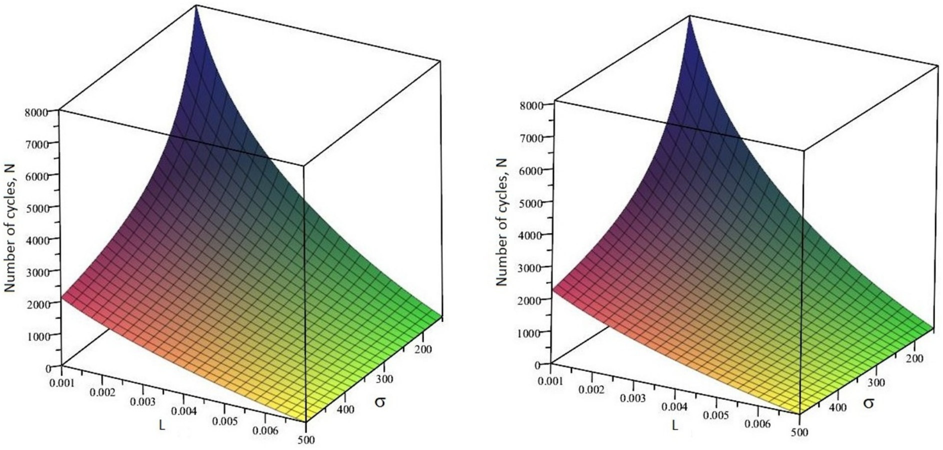
$$\frac{dL}{dN} = -13.4 \cdot 10^{-7} + 5 \cdot 10^{-7} \cdot \sqrt{K}. \tag{7}$$

The stress intensity coefficient K in formulas 6,7 depends on the geometric parameters of the defect, the operating stresses, and the wall thickness of the pipeline. If there is a crack on the surface of the pipeline, the K coefficient is calculated using the formula:

$$K = 1.122 \cdot \sigma \cdot \sqrt{\pi \cdot L} \cdot \left[\sec\left(\frac{\pi \cdot L}{2 \cdot t}\right)\right]^{1/2}. \tag{8}$$

Where σ – pipe wall voltage, MPa; L – crack depth, m;t – pipe wall thickness, m.

Determination of the residual life of a pipeline with a crack is carried out by integrating the dependence of the crack growth rate on the stress intensity coefficient according to dL (formulas 6, 7). Nomograms for determining the residual life of an oil trunk pipeline with crack-like defects are shown in Figure 3. Knowing the stress in the pipeline wall and the geometric parameters of the defect, it is possible to determine the number of cycles before the destruction of the metal structure.



a b

Fig. 4. Nomograms for determining the remaining life of the pipeline: a - in a carbonate-bicarbonate medium, b – in a carbonate-bicarbonate medium with a polarization of minus 0.7 V relative to the calomel reference electrode.

Experimentally, a decrease in the number of cycles to failure was established when polarization was applied, which is explained by the classical idea of the propagation of external polarization at the crack mouth and attenuation at the apex. When a cathode polarization of minus 0.7 V is applied relative to a saturated calomel reference electrode in an alkaline medium, the crack growth rate increases. Hydrogen embrittlement of steel in a carbonate-bicarbonate medium becomes the leading mechanism. The rate of hydrogen penetration increases with increasing cathodic polarization, which is observed in a carbonate-bicarbonate electrolyte at a potential of minus 0.7V relative to a saturated calomel reference electrode. A decrease in the number of cycles before destruction in a carbonate-bicarbonate medium is associated with the destruction of the passivating film, which can have a destructive effect under cyclic loads.

4 Conclusion

Thus, based on the study of the kinetics of crack development for VSt3sp steel under various operating conditions, it is possible to assess the crack resistance of steel and determine the residual life of metal structures. This method of forecasting the residual life of the pipeline metal takes into account changes in the geometric parameters of the defect and the internal pressure of the pumped petroleum product, takes into account the influence of corrosive media on crack growth, as well as the geometry of the equipment.

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