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Predicting pipeline life after an emergency repair

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Abstract. The operating conditions of main pipelines are analysed and it is established that fatigue and corrosion damage are the main causes of their destruction. The paper provides a substantiated answer to the question of the effectiveness of repairs using overlay elements. The number of load cycles that will take place before the destruction of the emergency section after repair with the use of overlay elements is determined by an example.

1 Introduction

The reliability of pipelines largely determines the continuity of industrial operations. According to statistical data, the number of pipeline failures in Ukraine tends to increase.

Failures occur mainly due to corrosion deterioration and ageing of pipelines, imperfect design solutions, factory defects in pipes, defects in construction and installation and repair works, by the fault of operating personnel and other reasons. A range of defects on the pipeline walls, group or continuous corrosion sores reduce the pipeline's load-bearing capacity.

Pipeline rupture accidents are relatively rare, but even a minor pipeline rupture can cause enormous damage due to environmental pollution, possible explosions and fires and loss of life. This is why maintaining the integrity of the pipeline's line section is one of the main challenges in pipeline transport.

Prompt and high quality elimination of the damage is of great importance, as pipeline failures are often accompanied by high economic losses and a long-term deterioration of the quality of environment.

The easiest and most common way to deal with emergencies on operating pipelines is to use various types of overlays. Modern overlay repair techniques have a drawback in reducing the safe operating life of pipelines and some of them can be used only as a temporary solution.

The existing methods for prediction of pipeline life including cyclic loading are based on the known Coffin-Manson low-cycle fatigue equation. In this work the method of low-cycle durability estimation of pipes with damage after emergency repair is applied for prediction of service life of gas pipelines.

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2 Current state of the researched issue

Numerous internal technical improvements have been developed and applied to avoid most failures in the day-to-day operation of onshore and offshore facilities.

Ukraine's gas transmission system has been in operation for an average of 30 to 52 years, depending on the age of its components. During its operation, a significant part of the main gas pipelines and process equipment have either exhausted their service life or have been subject to repeated maintenance and overhauls. Some have even become obsolete. The specified service life of gas pipelines and gas transmission system facilities requires significant investments to improve reliability and maintain them in a technically sound condition, as well as to comply with technological regulations for gas pumping.

Various organizations exist around the world to record pipeline failures. The purpose of these organizations is to systematize and analyse the causes of failures in gas pipelines.

In 1982, six European gas transmission system operators took the initiative to collect data on unintentional gas releases from transmission pipeline systems. This cooperation was formalized through the establishment of EGIG (European Gas Pipeline Accident Data Group). The aim of this initiative was to provide a broad basis for calculating safety indicators for pipeline systems in Europe, thus providing a reliable picture of the number, frequency and nature of incidents. Today, EGIG brings together seventeen European gas transmission system operators and has an extensive database of pipeline incidents collected since 1970.

According to the EGIG report, the causes of accidents on European gas pipelines are as follows (Fig.1):

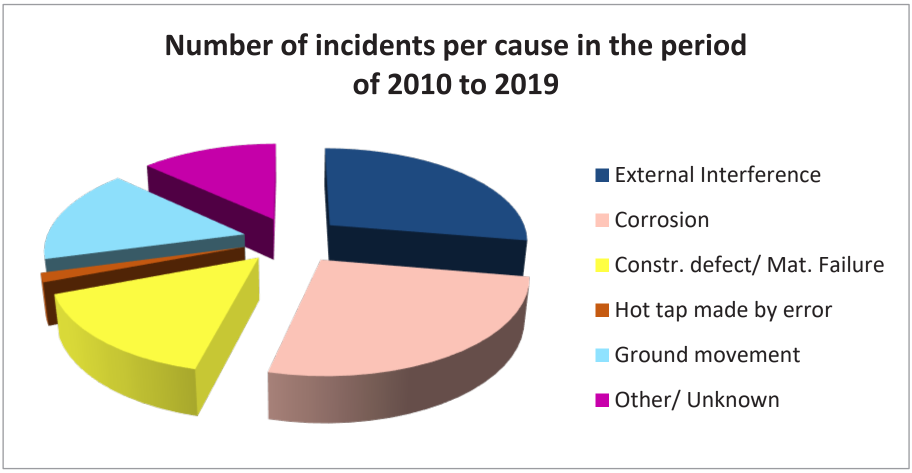

Fig. 1. Number of incidents per cause in the period of 2010 to 2019 (according to the report of EGIG [1]).

The diagram shows that one of the most common mechanical failures in a range of gas pipelines is caused by corrosion of equipment and systems.

A variety of causes and types of failures that are caused by corrosion have been investigated in the literature. Corrosion is a significant threat to pipeline systems, which can lead to leaks. Different types of approaches to analysis of corrosion causes have been studied in [2] for mechanical systems. Their findings have been used to predict accidents. Different types of accident assessments have been applied with regard to their specific features for different types of damage. Several scientific methods have been proposed to control the occurrence of cracks due to environmental influences with service life assessment criteria depending on the operating conditions [3].

Calculations for the strength of structural elements under long-term cyclic loads were given in [4], where defect-free materials and fatigue failure in the classical sense of this phenomenon were assumed. Experimental studies are also known, based on the results of which researchers constructed limit diagrams of the cyclic strength of structural elements with cracks, i.e. their residual cyclic strength [5, 6].

In studies [7], an automatic pipeline emergency assessment system has been developed, allowing the operator to interact with it. The capabilities of the emergency assessment system can be upgraded in conventional systems by obtaining data using spectral analysis and special instrumentation. In [8], authors have described various causes of pipe wall thinning and developed methods for repair and prediction of wall thinning rate based on measurement data. As a result of painstaking work, scientists from different countries were able to summarize and combine a variety of prediction methods for different types of pipes used in gas pipeline systems. A model for assessing the technical condition of submarine pipeline systems has been proposed in [9].

J.Z. Sikorska, M. Hodkiewicz, L. Ma considered the possibility of applying a three-level process business model for engineering problems. The proposed method allows selecting a suitable model to describe a three-level failure model [10]. In [11] an approach of plastic pipe fractures prediction using finite element method for 24-pipe with ring-shaped crack has been proposed. The construction of models based on statistical data for emergency assessment has been proposed in [12].

A simple model of crack growth in predicting accidents in gas transmission system using Bayesian interference and finite element method was proposed in [13]. On the basis of probabilistic methods a branch standard for prognosis of technical condition of mechanical systems was developed in Ukraine, and it is applicable to pipes as well [14]. Nowadays there are many new researches of tubing defects and pipeline emergency forecasts on the basis of statistical data with the help of different methods, taking into account various factors [15 - 21]. But the issue of operational reliability and durability of gas pipelines is very important, and therefore requires further detailed and in-depth study using new scientific achievements.

In Ukraine, important contributions to the problem was made by scientists such as A.B. Aybinder, P.P. Borodavkin, A.A. Korshak, V.V. Kurochkin, N.A. Malyushin, V.Y. Grudz, D.F. Timkiv, L.S. Shlapak, V.M. Ivashin, and E.I. Krizhanivsky, B.S. Bilobran. It should be noted that the research papers [22, 23] investigated the influence of operation parameters of a non-gas pipeline on its flow capacity, and the works [24, 25] describe the stressed - deformed state of line part of gas pipelines, problems of forecasting durability of pipelines due to low cycle stresses were considered. The Institute of Electric Welding named after E.O. Paton studied the problems of forecasting durability of pipelines taking into account low cycle stresses. The Paton Electric Welding Institute developed a method of welding multilayer inserts into a pipeline section made of single-layered pipes. When this section is destroyed by internal pressure, this method makes it possible to stop the avalanche crack propagation process in the multilayer inserts.

The process of stress corrosion cracking in existing main pipelines is spread over decades. Today, as the internal pressure and diameter of pipes increase, this process is becoming "younger", causing failure after 20 years or less of pipe service.

For the crack formation process to occur, the following factors must be present simultaneously

- sufficient cyclic stresses;
- a corrosive environment;
- a material that is incapable of resisting corrosion (pipe steels are such materials).

The process of crack initiation and development can be divided into three stages: initiation, propagation (stable slow and rapid catastrophic) and arrest. At each of these stages, once the fracture area is detected, it is subject to repair. One of the main repair methods is the use of overlay elements. Such repairs are considered temporary. Below we show that as a result of repair using overlay elements, the pipeline service life can be increased.

3 Residual life prediction

The Coffin-Manson low-cycle fatigue equation is the basis for existing methods for predicting the cyclic service life of pipelines. This equation relates the initial basic parameters – plastic strain amplitude ε_a and relative contraction ψ. In terms of being able to determine in practice an estimate of local value for ε_a for pipeline components is problematic due to the difficulty of finding the radius of curvature of most vertices of defects. This method is therefore appropriate for structural elements for which we can determine local values at the defect site ψ and ε_a. These difficulties lead to the fact that the regulated methods of calculation of low-cycle durability of pipelines, in general, should be referred to the category of theoretical ones, at least - for the objects of magistral pipeline transport. The above-said predetermines finding of other approaches to estimation of pipeline durability.

Let's consider laws of multi-cycle and low-cycle serviceability of metal with reference to pipe steels, taking into account peculiarities of stressed state of metal of structural elements of pipelines.

Metal fatigue will be understood as a degree of damageability of metal structure under repeated action of stresses. Stresses can be normal, tangential or equivalent. It should be taken into account that the limit stresses repeatedly applied to the most common carbon and low-alloy steels are several times less than the destructive stresses under single loading.

Most of the proposed low cycle fatigue equations relate the number of cycles to failure N, the plastic strain amplitude ε_{nl} and total strain amplitude ε_{np}. They are Orowan equation:

$$N\,\varepsilon_{nl} = const; \tag{1}$$

equation of Coffin-Manson:

$$N^{m_u}\varepsilon_{\mathrm{nl}} = C_{\mathrm{u}}, \tag{2}$$

where m_u and C_u are constants. Constant C_u is related to limit ductility of the material:

$$C_{\mathrm{u}} = \frac{1}{2}\varepsilon_{\mathrm{np}} = \frac{1}{2}\log\left(\frac{1}{1-\psi}\right), \tag{3}$$

where ψ – relative contraction at the breakage.

Substituting the summary strain amplitude $\varepsilon_a = \varepsilon_{nl} + \varepsilon_y$ in the equation of Coffin-Manson, where ε_y is an elastic strain amplitude, the equation of durability can be re-written in the following form:

$$\varepsilon_{\mathrm{a}} = \frac{1}{4}\sqrt[\frac{1}{m_{\mathrm{u}}}]{N}\cdot\varepsilon_{\mathrm{np}} + \frac{\sigma_{-l}}{E}. \tag{4}$$

Where σ_{-1} is a fatigue limit. Sometimes, this equation can be represented in relative strain coefficients:

$$\sigma_{\mathrm{a}}^{*} = \varepsilon_{\mathrm{a}}\cdot E = \frac{1}{4}\sqrt[\frac{1}{m_{\mathrm{u}}}]{N}\cdot\varepsilon_{\mathrm{np}} + \sigma_{-1}. \tag{5}$$

Degree m_u in these formulas depends on the mechanical characteristics of the metal. Steels with a high index m_u are characterized by a lower ratio of tensile strength to yield strength. For example, when increasing $\sigma_в$ from 700 to 1400MPa coefficient m_u changes from *0.50* to *0.65*. This relation is described (approximately) by a formula: $m_u=0.5+0.0002(\sigma_в -700)$. Let us note that parameter m_u correlates with a coefficient m. When $m < 0.15$ $m_u = 0.2$. When $m > 0.15$ parameter m_u depends linearly on the coefficient of strain hardening: $m_u = 0.2 + 2.4\ (m - 0.125)$ [26].

Manson, based on strain and force criteria, proposed a more general low cycle fatigue equation in amplitudes of total strain:

$$\varepsilon_a = SN^{-s} + TN^{t},$$

where S, s, T *and* t are material constants, while for many materials they are as follows:

$$s = 0.12; S = 3.5\frac{\sigma_в}{E}; t = 0.6; T = log\frac{1}{1-\psi}.$$

Longevity of an element is defined by integrating the equation

$$N_{mp} = \int_{h_0}^{h_{kp}} \frac{dh}{C_\sigma \cdot (\Delta K_{i\varepsilon})^{n_\sigma}}, \tag{6}$$

where h_0 and h_{kp} - initial and critical crack depths. The equation (6) can be represented in the following shape:

$$N_{mp} = N_0 \cdot K_n. \tag{7}$$

Where K_n in the first approximation equals to h_0/h_{kp}, N_0 is defined by the equation (7) when the initial value of coefficient of strain intensity $N_{mp}K_{i\varepsilon}^{(0)}$:

$$N_0 = \frac{h_{kp} - h_0}{C_\sigma\left(K_{i\varepsilon}^{(0)}\right)^{n_\sigma}}. \tag{8}$$

Taking into account K_n and $N=t/v$ this formula can be re-written as follows:

$$t_p = \frac{\delta_0 \cdot \eta_0 (n_h - 1)}{v \cdot n_h \cdot C_\sigma \left(K_{i\varepsilon}^{(0)}\right)^{n_\sigma}}, \tag{9}$$

where t_p is a time till an element is destroyed; δ_o is a thickness of element; $n_h = h_{kp}/ h_o$; v – frequency of load cycles.

Let's turn our attention to a practical example of calculations. Let a constructive element to function under periodic strain cycle with a maximum load σ_{max}, which equals to working load σ_p. Then, the working load equals to $\sigma_p=0.67\sigma_i$, namely $\sigma_p=201МПа$. Then a coefficient of strain hardening $m = 0.23$, and relative contraction $\psi = 52\ \%$.

With the specified initial data, the cyclic fracture durability parameters will be $n_\sigma= 1.23$ and $C_\sigma= 1.116 \cdot 10^{-4}$. According to diagnostic data, the initial depth of the fracture-like defect $h_0=3.8mm$. Then we find the critical defect depth corresponding to the operating load σ_p. The steel 17ГС is a plastic material with a parameter of fracture resistance $\alpha_{тр}$ [26] equals to 1 ($\alpha_{тр}=1.0$). This suggests that an element (pipe) with an extended crack-like defect will fracture at pressures that produce average stresses in the weakened model section close in magnitude to the time resistance of the metal $\sigma_в$. In other words, the strength of such elements will depend proportionally on the degree of weakening of the wall:

$$\sigma_{\text{нв}} = \sigma_{\text{в}}^{0M}\left(1 - \frac{h}{\delta_0}\right). \tag{10}$$

Let us substitute σ_{HB} with a value of work load σ_{p}, we get $h_{\text{kp}} = 9.8mm$. The relative depth of the defect is $\eta_{\text{kp}} = 0.71$, and the initial value $\eta_0 = 0.275$.

Then, let us find a coefficient of strain intensity $K_{\text{iε}}$. Under $\eta_0 = 0.275$ according to GOST 25.506-85 (State standard), let us find a correction function $Y_5 = 2.85$. Then, a coefficient of strain intensity will be equal to

$$K_i = 201\sqrt{0.0038}\cdot 2.85 \approx 35MPa\sqrt{M}. \tag{11}$$

Namely:

$$K_{i\varepsilon} = \left(\frac{35}{300}\right)^{\frac{2}{1+0.23}} \approx 0.0304\,. \tag{12}$$

Taking into account the value found for $K_{\text{iε}}$, let's use the formula (12) in order to find $N_{\text{тр}}$:

$$N_{mp} = \frac{3.8}{9.8}\frac{(9.8-3.8)\cdot 10^{-3}}{1.116\cdot 10^{-4}\cdot (0.0304)^{1.23}} \approx 1531\text{cycles}.$$

This number of cycles is valid, if the starting condition is a zero number of cycles: $P_{\min}=0$; $P_{\max}=P_{\text{p}}$, where P_{p} is a work load ($P_{\text{p}}=3.35$MPa). A reduction in amplitude of the strain rate factor by a factor of two results in an almost 2.5 - fold increase in durability. At frequency of loading cycles η = 365 cycles /year, we obtain a calendar time estimate till destruction t_{p}= 4.2year. Thus, the parameters of the kinetic equation of low-cycle crack resistance have been estimated and formulas for calculating the lifetime of elements with crack-like defects have been obtained.

4 Conclusions

The article analyses the operating conditions of magistral pipelines and establishes that fatigue and corrosion-fatigue damage are the main causes of their destruction. The existing methods for predicting the durability of pipelines require improvement, as they cannot fully take into account all operational factors.

The use of a system of comprehensive monitoring of the technical condition of magistral welded pipelines and timely repair of its parts will reduce the level of premature corrosion wear of components, increase the overhaul period of technological equipment and increase the level of its safe operation.

The article sought to answer the question of how successful the use of overhead elements is in pipeline repair. A specific example is used to demonstrate an algorithm for determining the residual service life of a pipeline after repair.

Thus, the article solved an urgent scientific and technical problem by using the Coffin-Manson equation to prove the effectiveness of repairing gas pipeline defects with the help of overlay elements and established that the number of cycles that will pass before the defective section of the pipeline is destroyed is several years.

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