INFLUENCE OF MULTIPLE HYDRAULIC SHOCKS OF OIL FLOW ON SAFE OPERATION OF PIPELINE TRANSPORT

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Abstract
Finite element modeling of the stress-strain state of the linear section of the pipeline under non-stationary force load was carried out to determine its residual life. Calculations were performed for the X60 pipe steel of an oil pipeline with an internal surface crack under turbulent oil flow and hydraulic shock. It was established that hydraulic shocks reduce the residual life of the pipe almost 2 times compared to laminar oil flow. Therefore, they should be taken into account to guarantee the reliable operation of pipeline transport.

Keywords Oil pipeline · Surface crack · Stress-strain state · Turbulent flow of oil · Hydraulic shock · Residual life · Safety · Pipeline transport

Introduction

It is difficult to determine the residual life of an oil pipeline pipe with an internal surface crack under the turbulent flow of oil and multiple hydraulic shocks. According to the results of the accident detailed analysis [1–5], it is possible in many cases to establish the direct connection between the fracture initiation sources and any, even inconspicuous metallurgical, production, construction, installation or operational defects, which are the stress concentrators on the inner and outer pipe surfaces. Factory defects are caused by non-metallic inclusions in the sulfides composition, cavities, incomplete removal of residual weld stresses, and mechanical damage of the pipe inner surface. Mechanical damages in the form of dents, nicks, scratches, as well as defects of transverse weld joints, in particular faulty fusions, etc., prevail during the mounting of pipelines and pipes transportation to the destination station. An internal surface crack can appear on the pipe wall as a result of corrosion and material fatigue, and propagate under the influence of the turbulent flow of oil and multiple hydraulic shocks during the change of pipeline operating modes. Corrosion can also contribute to the hydrogen charging of steel in the volume of the pipe wall, and therefore accelerate the steel structure degradation under the combined action of mechanical stresses, cathodic protection, and hydrogen absorbed by the metal [6–9]. In addition, the risk of hydrogen and corrosion cracking of pipeline steels according to the hydrogen embrittlement mechanism increases [3, 10–15]. However, it is difficult to determine the residual life of the pipe with a crack.

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First, it is difficult to establish the exact size and shape of the crack, since it is irregular and dimensions vary over time. Secondly, it is necessary to understand the corrosion and fatigue mechanisms of the material to predict the crack behavior under the influence of the turbulent flow of oil and hydraulic shocks. For this, it is necessary to model the hydrodynamic conditions in the pipeline and take into account the corrosion and fatigue influence on the material strength.

Non-destructive test methods (ultrasonic examination, X-ray tomography, etc.) can detect cracks, and determine their size and characteristics, and numerical modeling can reveal the influence of turbulent flow of oil and material fatigue on their size and propagation rate [16–20]. In general, it is necessary to combine experimental, numerical, and analytical approaches to calculate the residual life of a pipe with an internal surface crack under the turbulent flow of oil and multiple hydraulic shocks.

Therefore, it is important to build a mathematical model for predicting the crack growth kinetics and establish the responsible structural elements life between two periodic diagnostic inspections. The purpose of this research is to create a calculation model of crack growth in steel, to calculate the residual life of a pipeline with a surface semi-elliptical crack.

Problem Formulation

Let us construct a calculation model of an internal surface semi-elliptical crack with semi-axes a, b propagation in the pipe wall, and determine the time $t = t_{cr}$ until its depressurization, where r is the pipe radius; h is its wall thickness (Fig. 1a) to evaluate the residual life of the oil pipeline section (time until its depressurization) in the shunting mode under the turbulent flow of the oil, and possible hydraulic shocks. It is believed that t_{cr} is the time of the pipeline safe operation.

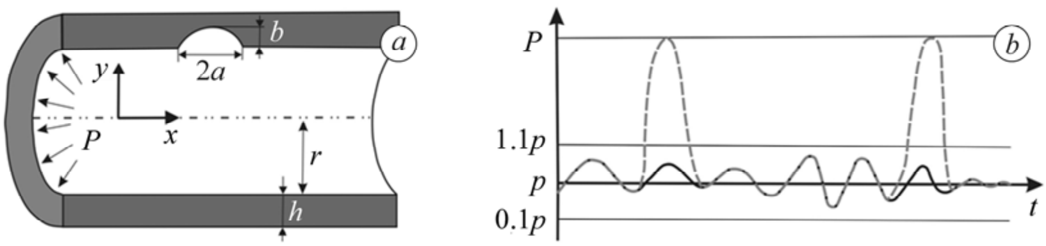

Fig. 1. Diagram of loading of an oil pipeline pipe with (a) an internal surface crack and (b) schematic representation of loading modes: solid curve – without consideration of hydraulic shocks; dashed curve – with consideration of hydraulic shocks.

It was assumed that the pressure p changes sinusoidal with the frequency of 0.3 Hz, and stress ratio $R = 0.97$ taking into account the turbulence flow of the oil inside the pipe. However, the pipe load may increase due to the shunting of the oil pipeline-operating mode. It includes rapid closing or opening of safety or stop-control valves, fault of automated technological process control systems, false activation of technological protections, periodic stops, restarts, etc., which can lead to hydraulic shocks with amplitude P (Fig. 1b).

It was assumed that during the crack growth, the n of such additional hydraulic shocks concentrated in time occur. It is necessary to determine the residual life of such a pipe under these conditions, that is, the time $t = t_{cr}$, when the crack will grow through the pipe wall and it will depressurize (Fig. 1a).

Residual Life Assessment

The residual life $t = t_{cr}$ of the pipe X60 steel was calculated for the following crack geometry and force loading: $r = 0.7$ m, $h = 0.02$ m, $p = 9$ MPa, $P = 12$ MPa; (Fig. 1b). The pipe characteristics were as follows: $\sigma_{YS} = 425$ MPa, $\sigma_{UTS} = 545$ MPa, $\Psi = 73\%$, $\delta = 23\%$, $K_{1C} = 231$ MPa$\times$m$^{-1/2}$.

The finite element method was used to solve this problem. The pipe with an elliptical crack was modeled using the ANSYS 2019R1 software. The 419517 tetrahedron-shaped elements connected by 627422 nodes were used to form a finite element mesh with crowds around the crack. As a result, the stress-strain state of the pipe was determined and the distribution of equivalent strains (Fig. 2*a*) and stresses (Fig. 2*b*) around the crack was obtained. It was established that when the load reaches the upper sinusoidal amplitude (Fig. 1*b*), the stresses around the crack increase beyond the plastic limit, due to which the deformations become irreversible, that is, they increase somewhat, in particular, around the crack in the pipe radial direction.

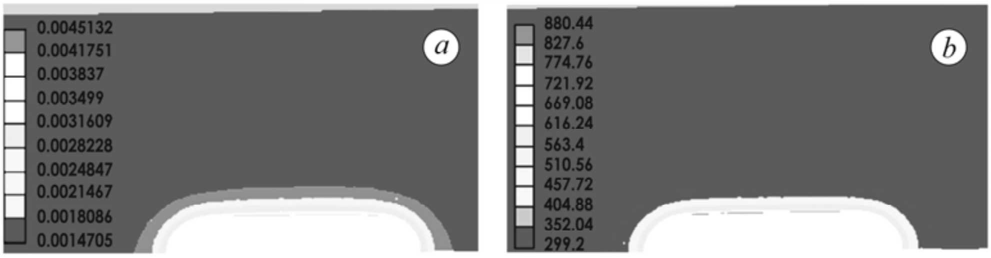

Fig. 2. Distribution of (*a*) equivalent deformations and (*b*) equivalent stresses around an elliptical crack.

A dimensionless parameter Δ was introduced for life prediction:

$$\Delta = \frac{b}{h} + d\varepsilon_y ,$$

where $d\varepsilon_y$ is the increment of deformation along the pipe thickness in the direction of axis y (Fig. 1*a*).

It was believed that the pipe will fail if $\Delta \approx 0.8$, that is when the pipe wall thickness around the crack is no longer able to withstand the operating conditions, as a result of which the pipe depressurizes. The dependence of the residual life (time until pipe depressurized) on the parameter Δ under the stationary mode (see Fig. 1*b*, solid curve) was plotted (Fig. 3, curve *1*), and time $t_{cr} = t$ ($\Delta \approx 0,8$), which was considered the operational life of the pipe, was determined.

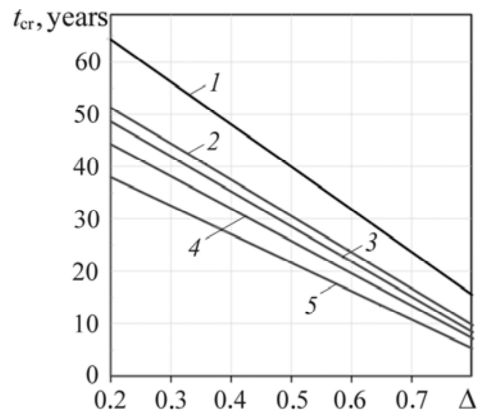

Fig. 3. Residual fatigue life t_{cr} of an oil pipeline pipe dependence on the dimensionless initial crack size Δ in (curve *1*) stationary and (curves *2–5*) shunting operating modes for different values of the hydraulic shocks number n per year: (*1*) $n = 0$; (*2*) 200; (*3*) 250; (*4*) 350; (*5*) 600.

Similar calculations were performed for the oil pipeline taking into account the shunting of the load (see Fig. 1*b*, dashed curves) for the number of hydraulic shocks $n = 200$; 250; 350, and 600 (Fig. 3, curves *2–5*).

CONCLUSIONS

A calculation model for determining the residual life of structural elements with internal surface cracks was formulated. The time dependence to fracture on the crack relative depth and the residual life of the oil pipeline section with a surface semi-elliptical crack were determined using the finite element method. The direct dependence of the pipe residual life on semi-elliptical crack depth and the number of hydraulic shocks was revealed. In particular, with an increase in the crack depth, the pipe residual life decreased in more than 4 times. Residual life for the crack depth, which equals 20% of the pipe wall thickness, under the number of hydraulic shocks from 200 to 600, decreased by 21–42%, and for the crack with a depth of 80% of the pipe wall thickness, decreased by 40–64%. This must be taken into account to guarantee the safety of the pipeline transport operation.

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