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Lifetime Estimation of High Density Polyethylene Pipelines Based on Fracture Mechanics Principles

Vlad Ulmanu, Gheorghe Drăghici, Virgil Aluchi

Universitatea Petrol – Gaze din Ploieşti, Bd. Bucureşti 39, Ploieşti
e-mail: vulmanu@upg-ploiesti.ro

Abstract

The paper presents a method for estimating the overall life of High Density Polyethylene pipes used for natural gas distribution, applying fracture mechanics principles.

The material properties – fracture toughness and the crack propagation rate are experimentally determined by testing Compact Type (CT 100) specimens machined from a polyethylene pipe wall. The crack propagation tests have been performed by tensile loading the specimens at various testing speeds, measuring the crack propagation speed and the corresponding tensile force. By applying the linear elastic fracture mechanics principles, the experimental results are used to determine the crack growth law.

The overall life of the pipe loaded by internal pressure is calculated by integrating the crack growth equation, using a specialized software elaborated by the authors, based on the procedure recommended by API 579 – 2/ASME FFS – 2 – 2009 Fitness for Service Example Problem Manual.

Key words: *polyethylene pipes; fracture mechanics; life estimation*

Introduction

Fracture mechanics offers a modern approach for lifetime estimation of mechanical structures by analyzing the crack initiation and propagation at flaws.

The failures of high density polyethylene (HDPE) internally pressurized pipelines shows that the damage process consists in initiation and slow quasibrittle crack growth originated in pipe manufacturing defects, weld seam flaws, partially welded pipes, defects induced by a third part and installation defects like additional local loading due to laying the pipeline without sand bed.

It is generally accepted that the failure of HDPE pipelines loaded by internal pressure presents three different failures modes, depending on the stress levels, figure 1 [4, 5, 6, 9]. At high stress levels (high internal pressure) the failure produces after short periods of time in a ductile manner, region I. This kind of failure is specific for pipes with local defects like smaller wall thickness than standard value. At smaller levels the failure produces after longer operating time in a quasibrittle manner by crack initiation at local defects and slow crack propagation to a critical size with local plastic deformation at the crack tip, region II. The region III corresponds to small stress values and long lifetimes, responsible for failure being the polyethylene ageing and degradation conducting to a brittle behavior.

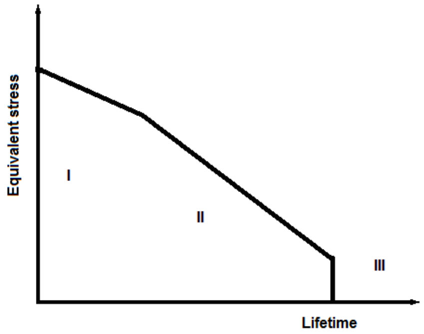

Fig.1. Domains of different failure modes of HDPE pipelines

The long term performance of HDPE pipe loaded at stress levels corresponding to region II of the diagram presented in figure 1 can be estimated based on fracture mechanics concept due to the same failure mechanism and kinetics in polyethylene pipes like in short term testing of HDPE samples for fracture mechanics approach.

The paper presents a method to predict the long-term performance of polyethylene pipes used for natural gas distribution based on short-term crack growth kinetic tests and linear elastic fracture mechanics concepts.

Fracture Mechanics Material Properties

Fracture mechanics has the possibility to determine the real material properties independent of the shape of the specimen.

In order to estimate the lifetime of HDPE pipes the fracture toughness and the crack propagation rate were experimentally determined for PE 100 polyethylene used in Romania as pipeline material for natural gas transportation. The samples were machined from a SDR 11 pipe with 355 mm external diameter and 34 mm wall thickness.

The fracture toughness was experimentally determined by testing a compact tension CT 100 specimen following the ASTM E 399 and ASTM 1820 specifications. The fracture toughness value is $K_{Ic} = 0.743\ \mathrm{MPa}\sqrt{\mathrm{m}}$ [1].

The crack propagation rate was experimentally determined using the following procedure, [1]:

- compact tension specimens with dimensions according to ASTM E 399, figure 2, were cut from the wall of the HDPE above mentioned gas-pipe;
- initiation of a crack at the bottom of the CT 100 V-shaped notch by using a razor blade;
- two V-shape channels were machined on both faces of the CT 100 specimen in crack propagation direction in order to maintain a plane crack tip displacement;
- the crack propagation rate was determined by loading four CT 100 specimens with different loading speeds (1, 2, 25 and 50 mm/min) and measuring the load, the displacement of the centers of the loading pin holes and the crack length.

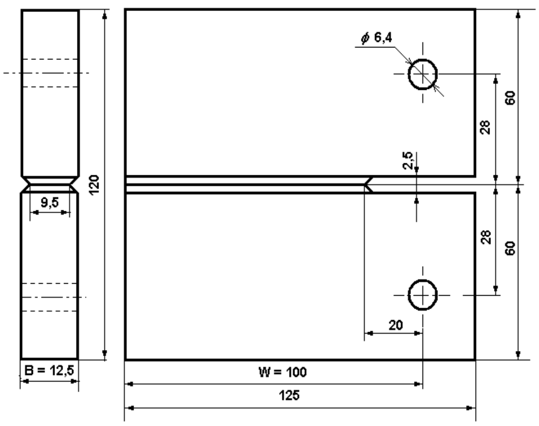

Fig.2. Geometry of CT 100 specimen

The crack growth rate is described by the following power law, [1]:

$$\frac{da}{d\tau} = 5.54 \cdot 10^{-8} \cdot K_I^{4,66}, \tag{1}$$

where a is the crack length;

τ – time;

K_I – stress intensity factor.

The experimentally obtained equation is in very good agreement with other observations on creep crack growth in polyethylene [10]

Lifetime Estimation of Polyethylene Pipelines

The pressurized pipelines are supposed to hoop stresses, static or variable. The inherent local defects in PE pipes act as stress raisers representing the place responsible for crack initiation and propagation. The most dangerous defects are those oriented perpendicular to the circumferential stress.

An already initiated crack at a stress concentrator will stable propagate until one of the following two failure modes are reached:

- sudden failure of the pipe when the applied stress intensity factor K_I describing the local crack tip stress, approaches the material's fracture toughness K_{Ic} and crack propagation becomes unstable;
- the crack penetrates the whole wall thickness and the pipe becomes untight.

Neglecting the crack initiation phase, difficult to estimate for PE pipes, a conservative estimation of the total life is obtained calculating only the crack propagation duration. The crack propagation duration is calculated by integrating the crack propagation rate experimentally determined , equation 1, over prescribed crack depth:

$$\tau = \int_{a_0}^{t} \frac{da}{5.54 \cdot 10^{-8} \cdot K_I^{4.66}} \tag{2}$$

where a_0 is the initial crack depth and t is the wall thickness of the pipe

For lifetime estimation of the PE 100 pipeline (355 mm diameter and 34 mm wall thickness) the pipe was supposed to present an external longitudinal crack having the depth to length rate a/c = 1/32 = ct., figure 3.

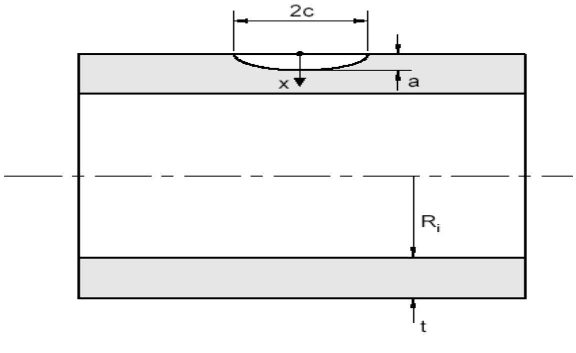

Fig. 3. External longitudinal crack in the wall of a pipeline

The stress intensity factor is calculated based on the methodology presented in [11] using the equation:

$$K_I = \frac{pR_i^2}{R_0^2 - R_i^2}\left[2G_0 + 2G_1\left(\frac{a}{R_0}\right) + 3G_2\left(\frac{a}{R_0}\right)^2 + 4G_3\left(\frac{a}{R_0}\right)^3 + 5G_4\left(\frac{a}{R_0}\right)^4\right]\sqrt{\frac{\pi a}{Q}} \qquad (3)$$

where p is internal pressure, R_i – internal radius of the pipe, R_0 – external radius of the pipe, a – crack depth (see fig. 3), Q – is determined using equation:

$$Q = 1 + 1{,}464x^{1{,}65} \qquad (4)$$

where $x = a/c$.

For a point of the crack tip the influence coefficients G_0 and G_1 can be determined using the following equation:

$$G_i = \sum_{j=0}^{6} A_{ij}\ , \qquad (5)$$

where parameters A_{ij} are provided in a table from [11] as a function of the ratios t/R_i , a/c and a/t (see fig. 3)

The influence coefficients G_2, G_3 and G_4 can be computed using the following equations [11]:

$$G_2 = q\left(\frac{16}{15} + \frac{M_1}{3} + 16\frac{M_2}{105} + \frac{M_3}{12}\right)$$
$$G_3 = q\left(\frac{32}{35} + \frac{M_1}{4} + 32\frac{M_2}{315} + \frac{M_3}{20}\right) \qquad (6)$$
$$G_4 = q\left(\frac{256}{315} + \frac{M_1}{5} + 256\frac{M_2}{3465} + \frac{M_3}{30}\right),$$

where:

$$q = \frac{\sqrt{2Q}}{\pi};\ M_1 = \frac{2}{q}(3G_1 - G_0) - \frac{24}{5};\ M_2 = 3;\ M_3 = \frac{6}{q}(G_0 - 2G_1) + \frac{8}{5} \qquad (7)$$

Based on this algorithm, a specialized software was elaborated by the authors using MathCAD to calculate the current values of the stress intensity factor K_I for a propagating longitudinal surface crack having a semi-elliptical shape in the wall of a polyethylene pipe internally pressurized.

The software is also dedicated to lifetime estimation of the polyethylene pipe having initial defect with different depths, a_0, loaded with different pressure values, p, by numerical integration of the equation (2). The integrating limits are from initial crack depth, a_0, to the wall thickness of the pipe, t = 34 mm. The estimated lifetimes are presented in Table 1.

The data presented in Table 1 show that the increasing of the operating pressure determine a more severe reduction of the estimated life of the pipe that the increasing of the crack depth. Thus, the increasing operating pressure from 1 to 4 bar reduce the lifetime 720…370 times, while increasing initial defect depth from 0.68 to 3.4 reduces lifetime 10…12 times.

Table 1. Lifetime estimation of a SDR11 PEHD pipe

***a/t* (*a*, mm)**	***p*, bar**	**τ, min**	**τ, years**
0.02 (0.68)	1	7.566E+7	144.0
	2	2.993E+6	5.7
	4	1.184E+5	0.2
0.05 (1.7)	1	1.958E+7	37.0
	2	7.743E+5	1.5
	4	3.063E+4	0.1
0.1 (3.4)	1	6.222E+6	11.2
	2	2.461E+5	0.5
	4	9.734E+3	0.02

Conclusions

A method has been proposed for estimating the total life of polyethylene pipes considered as notched member.

The life estimation is based on experimentally determined fracture mechanics material characteristics and on a software elaborated by the authors for integration of the crack growth rate equation.

The estimated total lives for a PE 100 pipe (355 mm diameter, 34 mm wall thickness) presenting external flaws (cracks) with different depths, loaded to different internal pressures, shows a drastically reduction in total life with increasing the crack depth and internal pressure.

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Estimarea duratei de viață a conductelor din polietilenă pe baza conceptelor mecanicii ruperii materialelor

Rezumat

Lucrarea prezintă o metodă de estimare a duratei de viață a conductelor din polietilenă de înaltă densitate, utilizate la distribuția gazelor naturale, prin aplicarea conceptelor mecanicii ruperii materialelor.

Caracteristicile de material necesare estimării durabilității – factorul critic de intensitate a tensiunilor şi viteza de propagare a fisurilor, s-au determinat experimental utilizând epruvete de tip CT prelevate din peretele unei țevi din polietilenă de înaltă densitate. S-au solicitat la tracțiune cu diferite viteze de solicitare patru epruvete, iar prin înregistrarea simultană a timpului, deplasării bacurilor şi valorii forței s-a determinat dependența dintre viteza de propagare a fisurii şi factorul de intensitate a tensiunilor.

Durata de viață a conductei solicitată cu presiune interioară, considerată până la momentul propagării fisurii pe toată grosimea peretelui țevii s-a determinat prin integrarea expresiei vitezei de propagare a fisurilor, elaborând un produs informatic dedicat ce are la bază procedura recomandată de standardul API 579 – 2/ASME FFS – 2 – 2009 Fitness for Service Example Problem Manual.