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Intrinsic Lifetime of Polyethylene Pipelines *

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Abstract

An equation was developed for calculating slow crack growth [SCG] failure in any polyethylene structure. The equation requires the following experimental inputs: (1) the resistance to SCG as measured by the PENT test (ASTM F1473), (2) the stress intensity of the defect from which failure originates, (3) the temperature. A simple experiment for determining the stress intensity is presented. The equation was applied to SCG failures that are associated with the inherent random defects that occur in the wall of all pipes. The size of the inherent random defect that exists in commercial gas pipes was found to be 0.14 mm.

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I. Introduction

Large scale usage of polyethylene pipe to convey natural gas began about 1965 by the DuPont Company. Today, millions of kilometers of PE pipe are carrying water and gas throughout the world. It is most important to know how long the pipes will last before they leak. Leaks are produced by a process known as “slow crack growth” [SCG]. The precursor to the crack is a craze that initiates at a point of stress concentration. The global stress surrounding the craze governs the rate of growth. The sources of greatest stress concentration occur at fittings, welded joints and rock impingements. However, throughout the pipe there are random defects that occur during the manufacture of the pipe. These defects also act as points of stress concentration from which cracks grow, but their stress intensity is much lower than those fore mentioned so that leaks from within the pipe occur at a much later time. During the service of the pipeline, leaks are constantly being repaired as they occur. However, when the leaks originate at the pipe wall, their number will be so large that the entire pipeline must be replaced.

In this paper, the time to failure of leaks that originate from random defects within the pipe is predicted, and the size of the largest random defect is calculated. Sandilands and Bowman [1] added particles into the pipe during the extrusion process. The lifetime of the pressurized pipe was reduced by a factor of twenty when the particle size was increased from 45 to200 μm. In this paper, it was determined that the average size of the largest random defect in commercial pipes is about 100 μm. The lifetime of the pipe line that is influenced by the defect depends on the cleanliness under which the pipe is manufactured. However, the major and the controllable factor that determines the life of the pipe line is the resistance of the resin to slow crack growth.

II. Fundamental Equation for Slow Crack Growth

The time, t, for failure by slow crack growth, [SCG], is a function of 5 variables.

$$t=F(R,a,Y,S,T) \tag{1}$$

R = resistance of the resin to SCG

a = size of the defect that produces the point of stress concentration

Y = geometric factor

S = global stress surrounding the defect

T = absolute temperature

Lu and Brown [2, 3] have shown that

$$t=R\,K^{-n}\exp[Q/RT] \tag{2}$$

The stress intensity, K, is the driving force given by

$$K= Y\,S\,a^{1/2} \tag{3}$$

n is a constant for a given resin and varies from 2.5 to 4.0; a value of 3 is most common. A theoretical derivation for n=3 has been developed by Brown and Lu [4]. Q is an activation energy whose value varies from 85 to 110 k j/mol depending on the resin and R is the gas constant. In order to make the prediction complete via Eq. (2), the resistance to SCG, R, must be quantified in terms of measurable quantities.

A standard test for measuring R in PE is the PENT test as described in specifications ASTM F1473 and ISO 16241. The PENT specimen in Fig. 1,which is made from a slow cooled compression molded plaque, has a single edge notch. The standard conditions for the PENT test are: notch depth, a=3.5 mm produced by a razor blade and a uniaxial stress, S=2.4 MPa. Y= 3.30 from Williams [5] and T=353 °K.. According to Equ. (3)

$$K(PENT)=0.468 \text{ MPa m}^{1/2} \tag{4}$$

The failure time for the PENT test according to Equ. (2) is

$$t(PENT)=R\ 0.468^{-n} \exp[Q/353R] \tag{5}$$

where 353°K is the temperature of the PENT test. Thus, the resistance to SCG,R, of a resin is proportional to its failure time in the PENT test where

$$R=t(PENT)(0.468)^{n} \exp[-Q/353\ R] \tag{6}$$

The failure time of any PE structure at temperature, T, under a stress intensity, K, whose resistance to SCG as measured by t(PENT) is obtained by combining Equ. (2) and (6)

$$t = t(PENT)[0.468/K]^{n} \exp[Q/R(1/T-1/353)] \tag{7}$$

The limitations on Equ. (7) are: (1). the concept of the stress intensity must not be invalidated by having too high a stress and too deep a notch that cause ductile failure, and (2). the temperature should be below 90°C. Usually 80°C is the highest temperature at which SCG is measured. As a general rule, the global stress surrounding the notch should be less than about 1/2-3/4 of the yield point at the temperature, T, depending on the notch depth. Too high a value of K will cause notch blunting and the structure will fail by a ductile mode instead of by SCG. Fig. 2 shows the effect of T and S on the failure time of pressurized pipe; Fig. 3 is for the PENT test. The regime of ductile failure is governed by t being proportional to S^{-25} and in the regime of SCG t is proportional to S^{-3}. The main difference between Fig. 2 and 3 is that the stress concentrator is much smaller in the pipe than in the PENT specimen. The failure time of a pipe by SCG depends on the largest random defect within the pipe wall.

There are other concerns with respect to Equ. (7). Note that the failure time in a manufactured structure is compared to that of the PENT specimen , whose standard state is a slow cooled compression molded plaque. The manufactured structure may have residual stresses , molecular orientation and a different lamellar size than the PENT specimen. Of over whelming importance in the use of Equ. (7) is that the manufactured structure consists of the same resin as the PENT specimen. The resistance to SCG depends on the molecular weight distribution, short branch chain density and its distribution with respect to the molecular weight. Variations in the molecular structure can change the failure time of SCG by a factor of 10^4 . The effect of processing variables, in the case of pipes for example ,may change the failure time at the most only by about a factor of about 2 as shown by Lu et al [6]. If the notch in the pipe is parallel to the direction of molecular orientation, then there is practically no difference between **R** in the PENT specimen and that in the pipe except for the presence of residual stresses. If the residual stresses are known they can be included in Equ. (7) as shown below.

III. Prediction of Failure in a Pressurized Pipe

When a pressurized pipe is part of a pipeline, the first failures in the pipeline originate at the points of highest stress intensity such as fittings, welded joints and rock impingements. SCG failures that originate from the inherent random defects within the pipe wall take a longer time by comparison. Long time ductile failures are not considered because they are never observed in the field. The life of the pipeline is prolonged by repairing leaks, but there comes a time when the leaks from the inherent defects within the pipe itself become dominant, and the pipeline must be replaced. The ultimate lifetime of the pipeline is determined by the PENT value of the resin and the stress intensity of the inherent defects within the pipe. There have been cases where hundreds of kilometers of gas pipeline had to be replaced because the PENT value was very low, on the order 1/3 hour. These cases occurred in the hottest parts of the United States as expected from Equ (7). There have been cases where short time failures originated at the wall of the pipe, which were produced by improper methods of extrusion. The inherent random defects, that are now being considered .exist in all commercial pipe that have been properly manufactured.

In order to predict the failure time from random defects in a commercial pipe, it is necessary to know their stress intensity. Lu and Brown [7] conducted an investigation from which the stress intensity of random defects in the pipe can be determined. The failure times of eight commercial pipes with different resins were measured at 80^{o}C under a hoop stress of 4.5 MPa. The PENT test was done on very same resin from each of the pipes. The PENT specimens were made from compression molded plaques They found

$$t(\text{pipe})=29 \pm 11 \ \ t(\text{PENT}) \qquad (8)$$

From Equ. (7) and since pipe test and PENT test were both done at 80°C

$$K(\text{pipe})= 0.468[t(\text{pipe})/t(\text{PENT})]^{-1/n} \qquad (9)$$

With Equ. (8) and n=3, Equ. (9) becomes

$$K(\text{pipe})=0.15\pm0.02 \text{ MPam}^{1/2} \qquad (10)$$

It is now possible to calculate the size of the largest random defect, within these commercial gas pipes, that causes SCG failure. The stress intensity of a very small notch(compared to the pipe thickness) on the inside wall of a fluid pressurized pipe was obtained from Rooke and Cartwright[8]. The results in Equ.(10) were obtained on 100 and 75 mm SDR 11 pipes under a pressure of 0.9MPa. so that K is given by

$$K= 5.98 \ (\pi a)^{1/2} \qquad (11)$$

where a is the size of the defect and 5.98 is the product of the Y factor(1.1) and the hoop stress of 5.4MPa. At the inner surface there is a residual tensile stress which exists in all extruded pipes.

Measurements of residual stresses by Broutman et al[9] found tensile values of 2 MPA at the inner wall. After long times at 80° C, the residual stress relaxed about 60%.to a value of about1.2 MPa Since K= 0.15 $MPam^{1/2}$ was obtained at 80^oC and under a hoop stress of 5.4 MPa, the total stress in Equ. (11) should be 6.6 MPA MPa by including the residual stress. Consequently the effective K value becomes $7.2\ (\pi\ a)^{1/2}$ .Now we can solve for a where

$$a = (0.15/7.2)^2\ 1000/\pi = 0.14 \text{ mm} \qquad (12)$$

The interesting question is "What is the lifetime of a pipe in the field when a leak originates from a defect of the above size?" The answer depends on the hoop stress, the average ground temperature and the PENT value of the resin.

The conventional hoop stress is equal to P(SDR-1)/2 where P is the pressure.. To initiate the calculation ,a hoop stress of 3.5 MPa will be used which is a common value for gas pipes in the USA . A residual stress of 1 MPa will be added to this conventional hoop stress in accordance with Janson[10] that the initial residual tensile of 2 MPa relaxes by about 50% after a long time at ground temperature.. Thus the effective K is proportional to 4.5 The previous value of K $=0.15MPam^{1/2}$,that was derived from the experiment by Lu and Brown[7], was obtained with a conventional hoop stress of 4.5MPa and with an effective stress of 5.7 MPa by including the residual stress. Consequently the value of stress intensity for the current calculation at ground temperature is

$$K= 0.15(4.5/5.7)= 0.12MPam^{1/2}. \qquad (13)$$

Assuming an average ground temperature of 10^{o}C and with n=3 and Q=90 k j/mol, the pipe lifetime is from Equ. (7)

t(pipe)=118,000 t(PENT) hours or 13 years of pipe life time corresponds to 1 hr of PENT.

The factor, 118,000 varies with the hoop stress and the average temperature of the pipe line. The primary control of the life time of the pipe depends on the choice of the resin with respect to its PENT value.

IV. Utilization of the Results

There are two situations:

(1). predicting the remaining life time of an existing pipe line, and (2). predicting the ultimate life time of a new pipe line. The prediction is based on the fundamental Equ (7). The lifetime of the pipe line in hours can be obtained by inserting the following values in Equ. (7) :

(1) the PENT value,(2) K=0.15 {(S+1)/4.5} MPam$^{1/2}$ where S is the conventional hoop stress, (3)the average ground temperature,(4) n=3 and (5) Q=90 kj/mol.

If the PENT value is not known for an old pipe line, remove a piece of pipe and compression mold it in accordance with ASTM F1473 and make a PENT test.. The remaining life is the predicted life minus the time the pipe line had been in service. There is no evidence that indicates that the PENT value, which depends on the molecular structure, changes with time at ground temperatures

. Temperature differences can give significantly different predictions. If the operating temperature is 20°C instead of 10°C the failure time would be 3.5 years for pipe failure per 1 hour of PENT instead of 13. The most important factor is the PENT value of the resin. There is currently much old DuPont pipe in the ground whose PENT value is about 1.5 hr; its predicted life time is about 50 years. There are cases where the PENT value of a pipe line was less than ½ hr and hundreds of kilometers of pipe line had to be replaced.

The current ASTM specification D2513 requires a minimum PENT value of 100hr. Thus, it is expected that pipe failures from inherent random defects within the pipe walls of new pipes will not occur before hundreds of years of service. The earlier SCG failures will originate at the points of high stress concentration such as fittings, welded joints, and rock impingements. In order to predict the failure time of a specific defects, it is necessary to know its stress intensity. It can be found by measuring the lifetime of the pipe with the specific defect at 80°C and comparing it with the lifetime of the same resin in the PENT test as was done by Lu and Brown [7].

V. Summary

The equation (7) was developed for predicting the time to failure by SCG of any polyethylene structure. The following inputs are required (1). the PENT value of the resin, (2).the stress intensity of the defect from which failure originates and (3). the ground temperature. In applying equation (7) residual stresses should be taken into account. A method is given for determining the stress intensity of a defect by comparing at 80° C the lifetime of the structure against the lifetime of the PENT specimen whose stress intensity is 0.468 $MPam^{1/2}$. The general equation was applied to the case of the inherent defects that occur in the wall of all commercial polyethylene gas pipes. It was determined that the size of the inherent defects in commercial PE gas pipes is about 0.14mm. The ultimate life time of a pipe line was calculated based on leaks from these inherent defects. Under average operating conditions, 13 years of life of a pressurized polyethylene pipe line was predicted for each hour of the PENT value of the resin.

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Figure Captions

1. Geometry of PENT specimen.

2. Failure Time vs. Hoop Stress in a Pressurized Polyethylene Gas Pipe at Various Temperatures (ref 11)

3. Failure Time vs. Tensile Stress in a PENT Specimen at various Temperatures (ref 2)