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Norman Brown

University of Pennsylvania, NBROWN@LRSM.UPENN.EDU

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Brown, N. (2007). Slow Crack Growth-Notches-Pressurized Polyethylene Pipes. Retrieved from https://repository.upenn.edu/mse_papers/142

Postprint version. Published in *Polymer Engineering and Science*, Volume 47, Issue 11, November 2007, pages 1951-1955.

Publisher URL: <http://dx.doi.org/10.1002/pen.20919>

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Slow Crack Growth-Notches-Pressurized Polyethylene Pipes

Norman Brown
Department Materials Science and Engineering
University of Pennsylvania, Philadelphia
e-mail nbrown@rsm.upenn.edu

Abstract

A general method for predicting the life time of a polyethylene structure that fails by slow crack growth was applied to the case of externally notched pressurized pipes. An analysis of experimental data indicated that the residual stress must be taken into account. The critical notch depths associated with a given life time were calculated as a function of pipe size, PENT value of the resin and temperature. The results were tabulated to serve as practical guide lines for deciding whether a pipe should be discarded if the notch is too deep. The current 10% of the thickness rule now used by industry was found to be invalid.

Introduction

A general method for predicting the lifetime of a structure that consists of linear polyethylene, [PE] and fails by slow crack growth, [SCG], has been developed by Brown (1). For example, SCG failures can be predicted in gas pipes where the failures originate at various points of stress concentration such as fittings, welds, rock impingements squeeze offs, defects within the pipe wall and surface flaws. In paper[1] the inherent life time was predicted based on the defect that are produced within the pipe during its manufacture. In this paper the relationship between the lifetime and the depth of an external notch was determined.

During installation, notches are produced in the pipe when it is dragged along the ground or inserted below ground in order to avoid having to dig a trench. The question arises as to how deep a notch should be allowed before the performance of the pipe is compromised. At the present time the industrial practice is based on a non-binding rule that the pipe should be discarded if the notch depth is more than 10% of the wall thickness. This rule was initiated by industry about 40 years ago and was based on experimental data which are no longer available. This investigation indicates that the 10% rule is very crude. This paper shows how the dependence of lifetime on notch depth varies with pressure, pipe geometry, quality of the resin and temperature. Tables are given for the critical notch depth versus life time, pipe size and temperature. Generally the absolute value of the notch depth is a more useful indicator of the lifetime than the percentage of the thickness. A major factor that determines the depth of the critical notch is the ratio of the desired life time of the pipe with respect to its resistance to slow crack growth as specified by the PENT TEST.

The Basic Equation for Slow Crack Growth in a PE Structure

The following theory is applicable to structures that consists of a linear polyethylene and that fail by slow crack growth. SCG failure generally occurs if the stress is less than about half the yield point at the operating temperature. All SCG failures originate at a point of stress concentration. The driving force for SCG failure is that combination of stress concentration and the global stress is called the stress intensity. The rate of SCG is thermally activated as governed by the Boltzmann factor.

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

$$t=F(R,a,Y,S,T) \quad (1)$$

R=resistance of the resin to SCG

a=size of the defect from which fracture originates

Y=geometric factor that depends on the ratio of **a** and a specimen dimension

S= global stress surrounding the defect including residual stresses

T=absolute temperature

Lu and Brown[2,3,] have shown that

$$t=R K^{-n} \exp[Q/RT] \quad (2)$$

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

$$K=Y S a^{1/2} \quad (3)$$

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 about 85 to 95 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** for PE is the PENT test as described in specifications ASTM F1473 and ISO16241. The PENT specimen is made from a compression molded slow cooled plaque and has a single edge notch. The standard conditions for the PENT test are: notch depth, **a**,=3.5 mm produced by a razor blade: uniaxial stress, **S**=2.4 MPa. **Y**= 3.30 from Williams[5] and **T**=353 °K. According to Eq.(3)

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

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

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

where 353 °K is the temperature of the PENT test. Thus, the resistance to SCG of a resin is proportional to its failure time in the PENT test, **t**(PENT). Note **R** is the gas constant.

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

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

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

A limitation on Eq.(7) is the concept of the stress intensity must not be invalidated by having too high a stress and too deep a notch that together cause ductile failure. 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 , and depends 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. The many investigations of long time failures in the field showed that practically all failures occurred by SCG.

Another limitation on the theory is caused by the difference in R between the PENT specimen and the manufactured structure whose lifetime is being predicted. The PENT specimen is in a slow cooled compression molded state where as the manufactured structure has a different microstructure depending on how it was processed e.g. extrusion or injection molding. The most important point is that the PENT resin and the manufactured product be of the same lot so that they have exactly the same molecular structure with regard to molecular weight distribution, short branch density and short branch distribution with respect to the molecular weight. These molecular variables exert the greatest influence on the resistance to slow crack growth as pointed out by Lu et al[6] and Trankner et al[7]. Another important factor is the residual stress which usually occurs in manufactured products. However, the residual stress is incorporated in the stress intensity and can be taken into account as shown below if its value is known. Another important factor is molecular orientation which may have a very large influence on R depending on whether the growing crack is parallel or perpendicular to the direction of molecular orientation. Work by Lu, Zhou and Brown [8] showed that if the crack grows perpendicular to the direction of orientation R increases significantly with the degree of orientation, but if the crack grows parallel to the orientation direction, R is practically independent of the degree of orientation and equal to that of the isotropic state. In the following application of the theory to a longitudinally notched extruded pipe the crack grows parallel to the orientation direction. Therefore, R in the PENT specimen and in the pipe are about the same as long as they are from the same lot of resin. There is still a relatively small difference between R in the PENT specimen and the

pipe which is caused by the difference in their rate of cooling from the melt.

Application of Theory to an Externally Notched Pressurized Pipe

The stress intensity for an external notch in a pressurized pipe as presented by Rooke and Cartwright[9] is presented in Fig(1) where

$$K = Y \left\{ \frac{2p R_1^2}{R_2^2 - R_1^2} \right\} \sqrt{\pi a} \quad (8)$$

Where the term in the brackets is the stress at the external surface produced by the pressure ,p. Y is a geometric factor that depends on the ratio of the pipe radii and the ratio of the notch depth and thickness of the pipe as shown in Figure 1. It is noteworthy that K is not a monotonic function of R_1/R_2 in accordance with the original calculation by Emery and Segedin(10) who discussed this particular point.

All extruded commercial pipes contain residual stresses. The magnitude of the residual stresses are comparable to the stress produced by the operating pressure in PE pipelines. Therefore the residual stress, S_r , must be included in Eq. (8) as follows

$$K = \left\{ Y \left[\frac{2p R_1^2}{R_2^2 - R_1^2} + S_r \right] \right\} \sqrt{\pi a} \quad (9)$$

The pressure stress is tensile, and the residual stress on the external surface of an extruded pipe is negative, compressive, and thereby ,it reduces the effect of the pressure stress.

There are many measurements of the residual stresses in pipes. In the case of polyethylene pipes the residual stress varies from compression at the outer surface to tension at the inner surface. Wong and Broutman[11] found that the residual stress varied with pipe size and with the extruder. Generally the tensile stress on the inside was about 2 MPa and the compressive stress on the outside about 3-4MPa. The paper reported in "Plastic Pipe Line"[12] investigated the effect of annealing on the residual stresses in pipe. Annealing at 80° C for 1,10 and 100 h reduced the residual stress 31,38 and 46% respectively. Measurements of the life time of a pipe at 80° C , whose purpose is to predict the life time at room temperature, must consider the fact that the residual stress at 80° C and at room temperature are not the same. The above theory will now be applied to experimental data.

Analysis of Experiments

The goal of the analysis is to compare measurements of the lifetime of pressurized pipes with external notches against the predictions based on equations 7 and 9. McKee et al [13] measured the lifetime of high density polyethylene SDR11 pipes at 80° C and a pressure of 0.50 MPa with notch depths equal to 30% of the thickness. The lifetimes shown in Table 1 are an average of three tests for each pipe size.

Based on Eq. (8), the K values are 0.227 and 0.312 MPam^{1/2} for the 60 and 114 mm pipes respectively. The effective K value must include the residual stress as in equation (9). This effective K value is inserted in Eq. (7). Note that the temperature factor is not involved because the PENT test and the pipe test were both done at 80° C. Now the residual stress can be determined from Eq.(7) with the following results: S_R is compressive and equals 1.10 and 1.25 MPa for the 60 and 114 mm pipe respectively. These results are consistent with room temperature measurements of about 3-4 MPa at the outer surface, and according to reference [11] are reduced by about 50% during the 80°C test. Note that these compressive residual stresses are very significant because they decrease the stress intensity by about 50% and therefore increased the life time by a factor of 8.

Another group of tests were organized at the University of Pennsylvania. The tests were done under the following conditions: 80°C, at a pressure of 0.9 MPa, outer pipe diameter of 100 mm, wall thickness of 0.909mm and notch depth 20% of the thickness. The test results are shown in Table 2, along with the calculation of the residual stress by means of Eq. (7) and (9).

These results are consistent with the expected values of the residual stresses and support Eq. (7) as a predictor of the life time of an externally notched pressurized polyethylene pipe as long as the residual stress is taken into account.

Dependence of Lifetime on Notch Depth

The effect of notch depth on the lifetime of pipes in the field under

typical operating conditions will be predicted. The notch depth for a given lifetime will be calculated as a function of the pipe diameter. The calculation will be based on the following conditions: an average temperature of 15°C one foot below the ground in the United States excluding Alaska, a maximum operating pressure according to ASTM D2513 which is 0.816 MPa, the most common value of the ratio of outer diameter to thickness which is SDR 11. Data by Wong and Broutman[11] show that the residual stress at the outer diameter is about 3MPa, and according to Janson[14] the residual stress decreases by about 50% in 10 years at field temperatures; therefore, for the following calculation, a residual stress of 0.8MPa will be estimated for a lifetime of 100years. This estimate is based on a logarithmic decrease of residual stress with time and Janson's observation of a 50 % decrease per decade. When the above parameters are inserted into Eq.(9)

$$K=0.14 t^{1/2} a/t]^{1/2} Y \text{ MPam}^{1/2} \quad (10)$$

Where a and t are in mm. Inserting Eq. (10) in Eq.(7) and letting n=3 and Q=90 kJ/mol.

$$t(\text{pipe})/t(\text{PENT})=[0.468]^3/[0.14(a/t)^{1/2} t^{1/2} Y]^3 \exp[90,000/8.31 (1/288 - 1/353)] \quad (11)$$

Note that the lifetime of the pipe is directly proportional to the PENT value of the resin. For the case of a PENT value of 100 hr, which according to ASTM D2513 is the minimum value for a gas pipe resin, and for a lifetime of 100 years(867000 hr), the notch depth, a, will be calculated as a function of the thickness, t, for an SDR 11 pipe. Consequently Eq.(11) reduces to

$$Y (a/t)^{1/2}=1.63/t^{1/2} \quad (12)$$

Eq(12) can now be solved for "a" as a function of t. From Eq.(12) a given value of t determines a value of the bracketed expression.. The relation of the bracket expression to a/t can be calculated from Fig1. Consequently, the dependence of a/t on t can be obtained. The results are presented in Table 3. The connection between t and the outer diameter of SDR11 gas pipes is listed in ASTM D2513.

The above calculation was repeated for the case of a 100 year lifetime and a PENT value of 500hr. There are pipes on the market with PENT values greater than 500hr. Equation. (12) now becomes

$$Y (a/t)^{1/2}=2.79/t^{1/2} \quad (13)$$

whose solutions are given in Table 4.

Note that the above results depend on the ratio of lifetime to PENT value and not on unique values of life time or PENT. As expected, the lifetime is directly proportional to the PENT value and increases as the notch depth decreases. The notch depth for a given lifetime increases non-linearly with pipe thickness. The relation of notch depth to thickness is not greatly affected in going from SDR 11 to about SDR 20.

The values of notch depth have an uncertainty based on the choice of n which may vary from about 2.4 to about 4. Also Q may vary from about 85 to 95 kJ/mol. It is estimated that these uncertainties will change the absolute values of the notch depth probably at the most about 25% but will not markedly change the form of the non-linear relationship between thickness and notch depth.

Discussion

The discussion will focus on the practical utilization of the results. The current guideline in industry is to reject a pipe if the notch depth is greater than 10% of the thickness. This is obvious a poor criterion since the notch which causes a certain lifetime is strongly non-linearly related to thickness and strongly depends on the PENT value. In order to decide what the critical notch depth should be for rejecting the pipe, the first step is to specify the desired lifetime. Next, knowing the PENT value of the resin, calculate the ratio of lifetime to PENT value which is now designated as the performance factor, PF which has the units of years of lifetime per hour of PENT. Table 5 shows directly how PF is related to the critical notch depth for a given pipe size. With a notch depth less than the critical value, the specified lifetime will be exceeded.

Tables 3, 4 and 5 should only be taken as guidelines for the operator to decide when a notch is too deep and the pipe should be discarded. The first step is that the operator determines his performance factor. The critical notch depth depends on the operating temperature of the pipe line. Note in Eq. (11) that the effect of temperature is contained in the exponential term and that PF, the ratio of lifetime to PENT, is proportional to the exponential term. The performance factor, PF, should be modified in accordance with the deviation in the operating temperature from the average value of 15°C. The above tables were calculated for a constant operating pressure of 8.61 bar. If the average operating pressure is less than 8.61 bar the lifetime will be increased. The increase in life time

depends on the ratio of the K values that are obtained by inserting 8.61 bar and the operating pressure in equation (9). The performance factor is modified by the fact that the lifetime varies inversely with the cube of K.

The tables 3,4 and 5 are for SDR 11 pipes. For other SDR values obtain the ratio of the SDR 11 K value with respect to the new SDR value using Eq. (9). Then modify the PF with respect to the dependence on the cube of the K value. The thickness of the pipe is practically more important than the pipe size. Thus, when using tables 3,4 and 5 use thickness rather than pipe size as the index for obtaining the critical notch depth.

Summary

The depth of an external notch in a pressurized polyethylene gas pipe was related to the life time terminated by slow crack growth. The critical notch depth depends on pipe geometry, pressure, residual stress, PENT value and temperature. The results are presented in tabular form as practical guidelines for the pipe line operator to decide whether or not to discard a pipe with a given external notch depth.

The current 10% thickness rule used by industry for deciding when to discard a pipe is simplistic because the absolute value of the pipe thickness, the PENT value of the resin and the temperature are the important factors.

The theory was supported by experimental data which indicate that the residual stress must be taken into account in order to predict the lifetime of a pressurized pipe.

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Table 1 Lifetimes of Pipes at 80° C

OD(mm)	Pipe Thickness(mm)	PENT(hr)	Life time(mm)
60.3	5.49	23.2	2200
114.3	10.39	39.0	2400

Table 2. Lifetime of Gas Pipes at 80°C

Material	PENT(hr)	Life time(hr)	Residual Stress(MPa)
HDPE	3.0	44	1.35
MDPE	9.3	294	1.87
MDPE	336	4072	1.20

Table 3. Dependence of Notch Depth on Pipe Diameter for 100 year Lifetime s for PENT Value of 100 hr, SDR 11, Pressure=0.816 MPa and T=15° C.

OD (inch)	t(mm)	$1.63/t^{1/2}$	a/t	a (mm)
1	3.02	0.94	0.33	1.0
2	5.49	0.70	0.25	1.4
4	10.39	0.51	0.16	1.6
6	15.32	0.42	0.12	1.8
8	19.94	0.37	0.10	2.0
10	24.84	0.33	0.08	2.1

12	29.46	0.30	0.07	2.2
24	55.4	0.22	0.04	2.3
36	83.1	0.18	0.03	2.5

Table 4. Same as Table 3 except a PENT Value of 500 hr

O D(inch)	t (mm)	$2.79/t^{1/2}$	a/t	a (mm)
1	3.02	1.61	0.50	1.5
2	5.49	1.19	0.40	2.2
4	10.39	0.87	0.31	3.2
6	15.32	0.71	0.25	3.8
8	19.94	0.62	0.21	4.2
10	24.84	0.56	0.18	4.5
12	29.46	0.51	0.16	4.7

24	55.4	0.37	0.10	5.5
36	83.1	0.31	0.07	5.8

Table 5 Dependence of Critical Notch Depth in mm ,on SDR 11 Pipe Size ,Pipe thickness and Performance Factor at15°C and Pressure of 0.861 MPa

Thickness(mm)	3.02	5.49	10.39	15.32	19.94	24.84	29.46
PF(yr/hr)							
2	0.8	1.1	1.2	1.4	1.6	1.6	1.7
1	1.0	1.4	1.6	1.8	2.0	2.1	2.2
0.5	1.2	1.8	2.2	2.6	2.8	2.9	3.1

0.2	1.5	2.2	3.2	3.8	4.2	4.5	4.7
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Figure Caption

Fig.1 Y versus a/t .

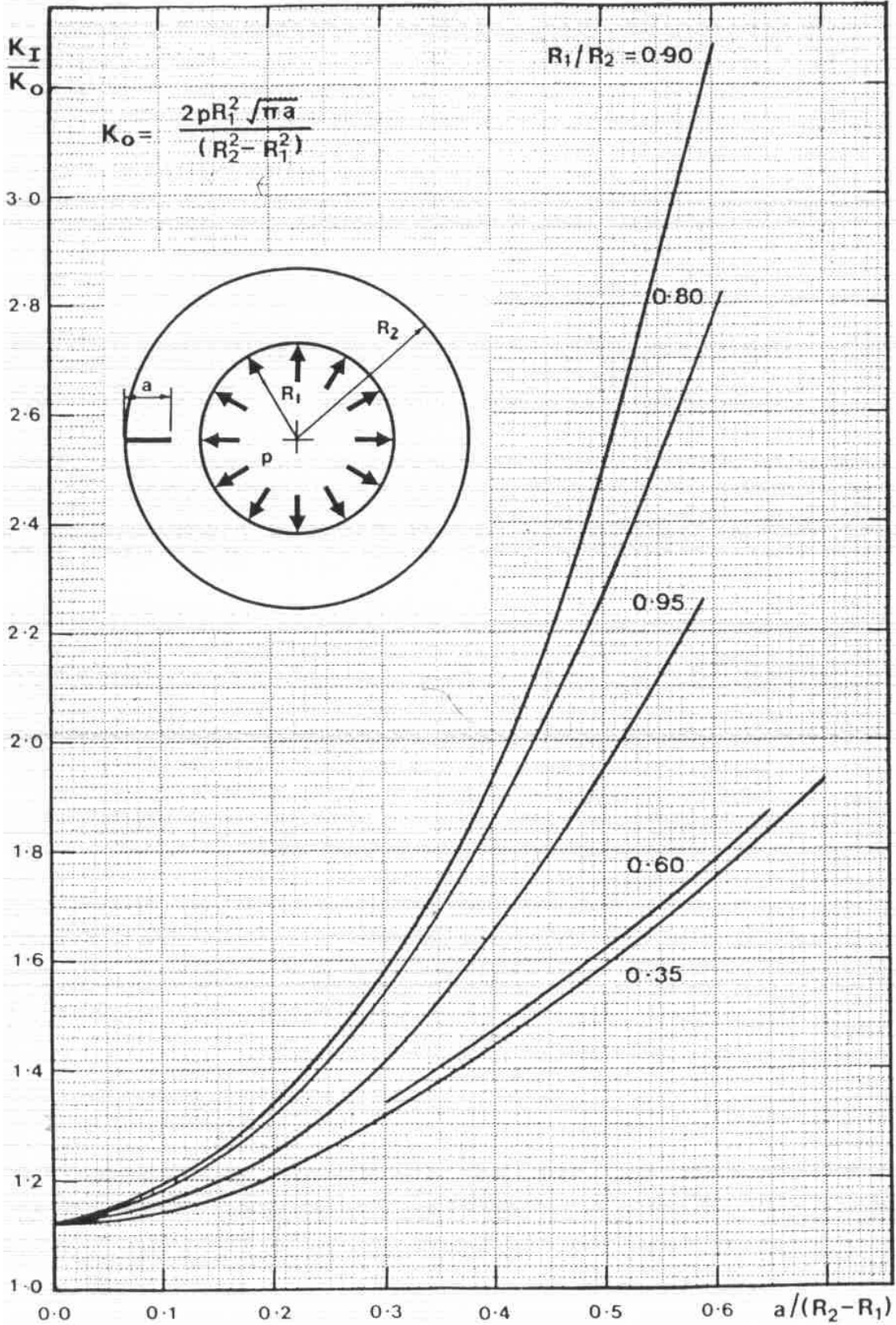


Fig.1 K_I for an external radial edge crack in a tube subjected to a uniform internal pressure

