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STRESS CORROSION CRACK GROWTH OF HIGH DENSITY POLYETHYLENE WITH CRACKED ROUND BAR SPECIMEN IN CHLORINE MEDIUM

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Abstract

In this study, the stress corrosion crack (SCC) growth model for the cracked round bar (CRB) specimen was developed. The axisymmetric crack layer (CL) theory for simulating the slow crack growth (SCG) behavior of CRB specimen was modified to consider the chemical degradation due to diffused aggressive environment. The diffusion of oxidative fluid into the process zone (PZ) in radial direction is considered. Also, the chemical degradation kinetics of PZ materials due to the oxidation were modeled. The proposed model was shown that the discontinuous SCG behavior and the deteriorative effect from the chemicals were successfully simulated.

Nomenclature

l_{CR}	Crack length
L	Crack layer length
R_o	Outer diameter of cracked round bar (CRB) specimen
X^{CR}	Thermodynamic force for crack growth
X^{L}	Thermodynamic force for process zone growth
J_I^{CR}	Energy release rate at the crack tip
J_I^{PZ}	Energy release rate at the process zone tip
2γ	Specific fracture energy
δ_{tot}	Crack opening displacement
γ^{tr}	Transformation energy density
λ	Natural drawing ratio
k_{CR}	Kinetic coefficient for crack growth
k_L	Kinetic coefficient for process zone growth
C	Concentration of diffused chlorinated water
r	Radial coordinate of cracked round bar (CRB) specimen
D	Diffusion coefficient
k	Influx coefficient
ω	Degradation degree
k_R	Reaction coefficient
t_{OIT}	Oxidation induction time
t^*	Characteristic time

Introduction

The improvement of mechanical and physical properties of high-density polyethylene (HDPE) materials encourage the broad applications to the pipe industry. The thermoplastic pipes including the HDPE has the flexibility, light-weight, and corrosion-free characteristics. Also, the HDPE pipe reveals the outstanding performance to the seismic loading than the steel and concrete pipes [1].

The HDPE pipes exhibit the three distinguished failure modes with regard to the applied hoop stress level as shown in Figure 1. At the high level of hoop stress, the pipe undergoes the localized large deformation and ballooning at the weakest point. A high sensitivity of the lifetime on the applied stress level causes somewhat uncertainty in this failure mode. At the intermediate stress level, the brittle fracture occurs with the crack initiation from the pre-existing defects and the slow crack growth (SCG). To understand the unique characteristics of the SCG behavior of HDPE, i.e., the discontinuous SCG, the crack layer (CL) theory was suggested and have been successfully applied to various geometries including pipe [2, 3].

When the thermoplastic pipes convey the oxidative fluid, e.g., chlorinated water, under the low level of mechanical stress, the chemical degradation dominates the pipe failure. Because of the diffusion limited oxidation, the formation of thin degradation layer at the inner surface and the multiple crack initiation is characteristic phenomena of this failure mode, so-called the stress corrosion cracking (SCC) (see Figure 2) [4]. After the crack initiation, the SCG accompanying the chemical degradation causes the final failure. In this stage, the lifetime is almost independent on the mechanical stress level, rather the lifetime becomes a function of the oxidation kinetics.

As the importance of the durability evaluation of the HDPE pipes in the chlorinated environment has emerged, the several accelerated test methods have been suggested to measure the resistance to the chlorinated water. Particularly, several methods have been proposed to evaluate the crack growth resistance in chlorinated water chamber, by using the lab-scale crack growth specimens, i.e., single edge notched tension (SENT), compact tension (CT), and cracked round bar (CRB) specimens [3, 5]. In particular, the CRB specimen is very useful because the brittle fracture can be generated even at the relatively high level of stress. Therefore, the test duration can be further shortened.

In this study, the SCC growth model for the CRB specimen was suggested. The existing axisymmetric crack layer (CL) model for the CRB specimen was modified in

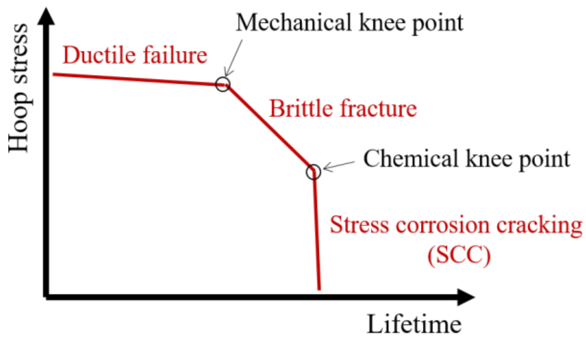

Figure 1. Failure modes of pressurized thermoplastic pipes with applied hoop stress level.

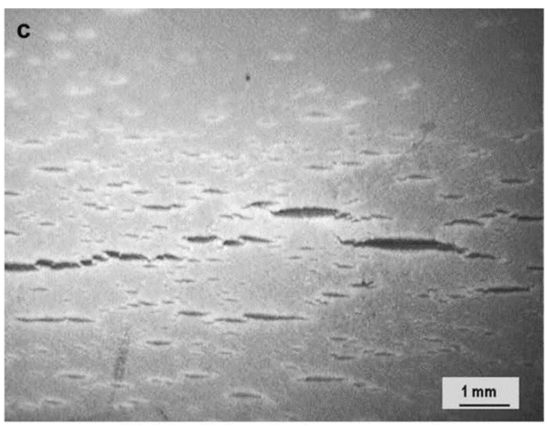

Figure 2. Multiple crack initiation in stress corrosion cracking (SCC) in polyethylene [4].

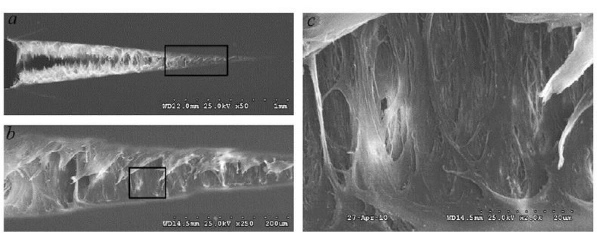

Figure 3. Crack tip and process zone (PZ) of high density polyethylene (HDPE) [3].

consideration of the oxidative degradation effect. The diffusion of the chlorinated water and oxidation with polymer medium were considered.

Theoretical backgrounds

In case of high density polyethylene (HDPE), the damage zone in front of the main crack tip is generally observed by the wedge shape. This damage zone, so-called process zone (PZ) consists of highly drawn fibrils (see Figure 3). Also, it has been widely observed that the HDPE reveals the discontinuous SCG behavior, due to the physical interaction between the crack and PZ. The crack layer (CL) theory. The thermodynamic forces for crack and PZ growth, X^{CR} and X^{L}, respectively, for the cracked round bar (CRB) specimen can be formulated by [5]

$$X^{CR} = J_I^{CR} - 2\gamma \tag{1}$$

$$X^{L} = J_I^{PZ} - \frac{\gamma^{tr}}{(\lambda-1)(R_o - L)} \frac{\partial}{\partial L}\left[\int_{l_{CR}}^{L} (R_o - x)\delta_{tot}(x)dx\right] \tag{2}$$

where the J_I^{CR} and J_I^{PZ} denote the energy release rate at the crack and PZ tip, respectively. The 2γ is the specific fracture energy at the crack tip, which decays with the crack arrest time. The l_{CR} and L are the crack and CL length, as shown in Figure 4. The R_o is outer radius of CRB specimen. The $\delta_{tot}(x)$ is the crack opening displacement within the PZ.

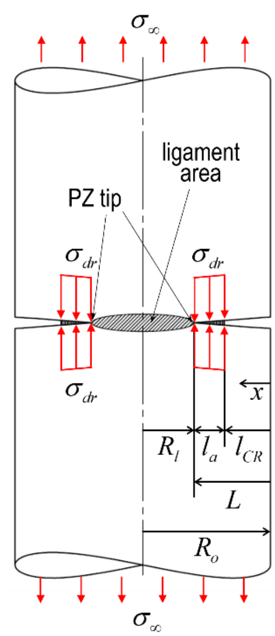

Figure 4. Crack layer (CL) system of cracked round bar (CRB) specimen [5].

The rate terms for crack and PZ growths can be written by linear relationship between the growth rate and corresponding thermodynamic force, i.e.,

$$\frac{dl_{CR}}{dt} = \frac{k_{CR}X^{CR}}{2\pi(R_o - l_{CR})} \tag{3}$$

$$\frac{dL}{dt} = \frac{k_L X^L}{2\pi(R_o - L)} \tag{4}$$

where the k_{CR} and k_L are the kinetic coefficients for crack and PZ growth, respectively. By using the time-marching loop, the evolution of CL system can be simulated numerically. It was demonstrated that the axisymmetric discontinuous SCG observed from the CRB specimen can be accurately simulated by the above CL model [5].

Stress corrosion crack growth model for cracked round bar (CRB) specimen

Diffusion in cracked round bar (CRB) specimen

The diffusion of chlorinated water at the crack tip in cracked round bar (CRB) specimen can be formulated by following radial diffusion equation (see Figure 5),

$$\frac{dC}{dt} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial C}{\partial r}\right) \quad (5)$$

where the $C(r, t)$ denotes the concentration of diffused chlorinated water. The r is radial coordinate as shown in Figure 6. Also, the evaporation boundary condition at the crack tip ($r=a$) was employed, i.e.,

$$-D\frac{\partial C}{\partial r} = -k[C(a,t) - C_\infty] \quad at \ r = a \quad (6)$$

where the C_∞ is a concentration of environmental chlorinated water. The initial condition was adopted by zero initial concentration, $C(r, 0)=0$.

Oxidation kinetics and process zone degradation

Due to the diffused chlorinated water, the polymer medium undergoes the oxidative reaction, resulting in the chain scission and degradation. Let the degradation degree ω be in the range from 0 (fully degraded) to 1 (undegraded). In this study, the simplified equation for oxidative reaction was adopted [4].

$$\omega(r,t_i) = k_R C(r,t)[t_i - t_{OIT}] \quad (7)$$

where the k_R is reaction coefficient. The oxidation induction time was also considered by using t_{OIT} (see Figure 7). The decay of the process zone (PZ) due to the mechano-chemical degradation was modeled by following superposition equation [4],

$$\frac{\gamma}{\gamma_0} = \left[1 - \left\{1 - \left(1 + \frac{t_i}{t^*}\right)\right\} - \{1 - (1-\omega)^{2.4}\}\right] \quad (8)$$

where γ_0 is initial specific fracture energy of undegraded material, and the t^* is characteristic time for mechanical degradation. The first and second term in RHS indicate the mechanical and chemical degradation of PZ, respectively.

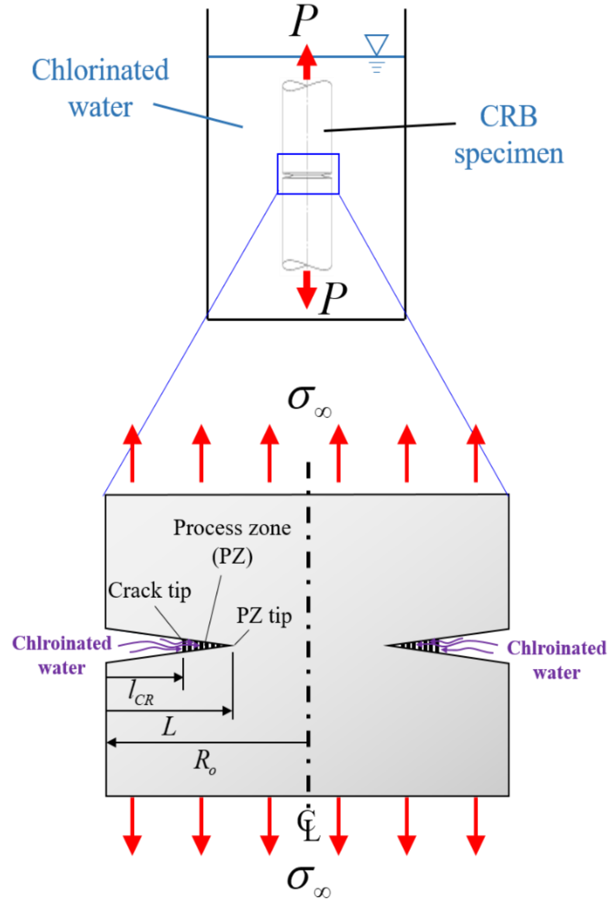

Figure 5. Cracked round bar (CRB) specimen within the chlorine chamber. The chlorinated water would diffuse into the process zone (PZ) with the oxidative reaction.

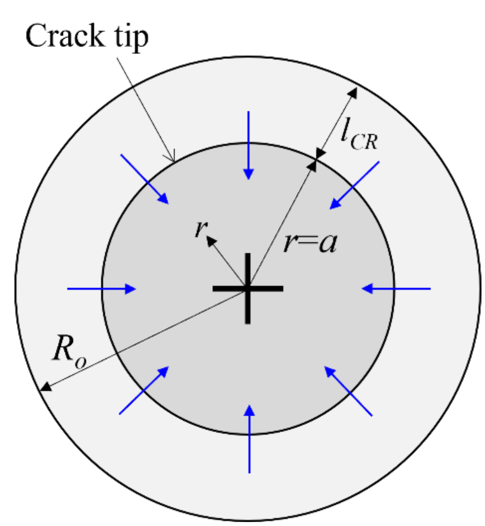

Figure 6. Diffusion of chlorinated water into the CRB specimen.

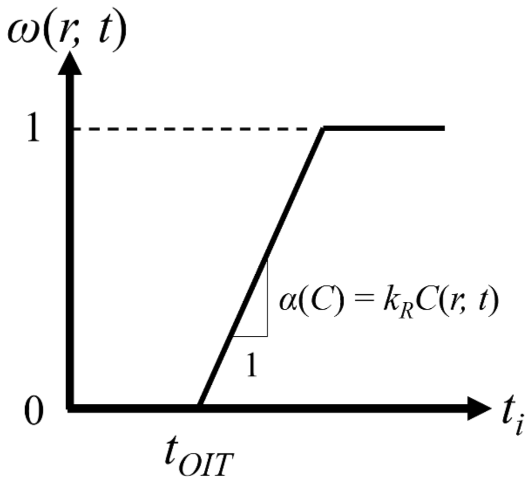

Figure 7. Degradation degree ω with the concentration of diffused chlorinated water C [4].

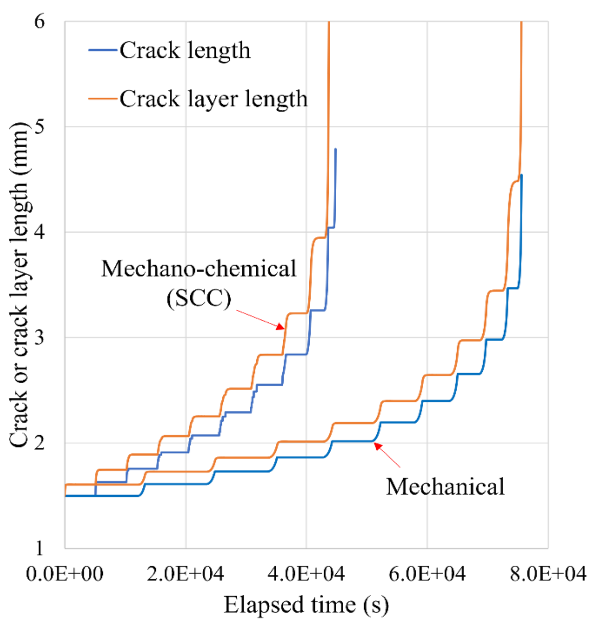

Figure 8. Crack and process zone (PZ) simulation of cracked round bar (CRB) specimen.

Crack growth simulation results

The cracked round bar (CRB) specimen with the outer radius of R_o=7 mm and initial crack length of 1.5 mm was considered. From the abovementioned stress corrosion crack (SCC) growth model, the discontinuous slow crack growth (SCG) was successfully simulated (see Figure 8). When there is no oxidation effect (k_R=0), the longer crack arrest times can be clearly seen, due to the slower decaying of 2γ in Eq. (8). However, the process zone (PZ) decays due to the mechanical creep as well as the chemical oxidation, i.e., mechano-chemical degradation, resulting in the reduced crack arrest times and final failure time. It was experimentally demonstrated that the fatigue-loaded HDPE CRB specimen emersed in the chlorinated water reveals faster crack growth rate and shorter lifetime than the same specimen in the pure water [6]. Thus the proposed model can be applied to understand the accelerated lifetime results in the chlorinated environment.

Conclusions

In this study, the stress corrosion crack (SCC) growth model for the cracked round bar (CRB) specimen was developed. The diffusion of the oxidative fluid into the process zone (PZ) during the crack growth duration was considered. The decay of specific fracture energy (SFE) of the PZ was modeled based on the superposition method, i.e., SFE decrease due to mechanical creep and chemical oxidation. The simulation results clearly showed that slow crack growth (SCG) under the mechano-chemical degradation reveals the reduced crack arrest times and final lifetime. The developed model can be used to simulate the CRB tests emersed in the chlorinate water, for the accelerated SCC resistance tests.

References

1. A. Chudnovsky, Z. Zhou, H. Zhang, and K. Sehanobish, *Int. J. Eng. Sci*., **59**, 108 (2012).
2. J. -W. Wee, S. -Y. Park, and B. -H. Choi, *Eng. Fract. Mech.*, **236**, 107205 (2020).
3. H. Zhang, Z. Zhou, and A. Chudnovsky, *Int. J. Eng. Sci.*, **83**, 42 (2014).
4. B. -H. Choi, A. Chudnovsky, R. Paradkar, W. Michie, Z. Zhou, and P.-M. Cham, *Polym. Deg. Stab.*, **94**, 859 (2009).
5. J. -W. Wee and B. -H. Choi, *Int. J. Solids Struct*., **97**, 189 (2016).
6. J. Fischer, P. J. Freudenthaler, P. R. Bradler, and R. W. Lang, *Polym. Testing*, **78**, 105998 (2019).