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Numerical modeling of stress corrosion cracking of polymers

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ABSTRACT

A unified chemo-mechanical model is developed to simulate stress corrosion cracking (SCC) of high density polyethylene (HDPE) in a chlorinated environment. The model consists of three components, each of which captures a critical aspect of SCC. A chemical kinetics–diffusion model is used to simulate the reactions and migration of chemical substances. The fracture behavior of HDPE is captured by a cohesive crack model, in which the cohesive properties are considered to be dependent on the extent of the chemical degradations. The time-dependent creep behavior of the bulk HDPE material is described by an elastic–viscoplastic constitutive model. This chemo-mechanical model is numerically implemented for finite element (FE) analysis of SCC of HDPE structures. The simulations show two different failure mechanisms depending on the applied stress level: at high stresses, the failure is primarily due to the excessive plastic deformation whereas at low stresses the chemical reactions and diffusion are the dominant factors leading to failure. In addition, examination of detailed crack growth kinetics reveals that at low stress levels the disinfectant concentration has a significant effect on the crack growth behavior through the relative dominance between the chemical reaction and diffusion processes.

1. Introduction

Polymers are increasingly used for structural applications owing to their corrosion resistance and low cost compared with metals. Typical applications of polymers for civil infrastructure (without reinforcing fibers) include: geomembranes, geogrids, pipelines for water and natural gas delivery, corrugated drainage pipes and sanitary pipes. Longevity of polymeric components is a critical aspect of these structures. However, exposure to an oxidative environment could lead to premature failure of the polymeric components. For example, geomembranes have been widely used to contain hazardous and waste liquid/solid and its long-term structural integrity is of great concern to designers. Accelerated testing, which uses a combination of high stress, elevated temperature and strong oxidizing agent, has been used to determine the long-term performance of geomembranes [26]. Disinfectants (oxidizers) in potable water can severely degrade the inner surface of plastic pipelines, causing substantial crack formation and eventually a complete failure. Service lifetimes of the failed water pipes can vary between 1 and 25 years, which are significantly lower than the expected lifespan of 50–100 years [12]. Published data for these applications have confirmed that the interaction between mechanical stresses and environment could significantly accelerate the polymer degradation and lead to crack formation and propagation, referred to as stress corrosion

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Nomenclature

$\bar{s}$	number of chain scission
$\bar{x}$	number of crosslinking
β	relative thickness
δ_c	critical cohesive separation at failure
$\dot{\Delta}$	load point displacement rate
$\dot{\varepsilon}^p$	uniaxial plastic strain rate
ε_{max}	maximum strain
ω	damage parameter
σ	uniaxial stress
σ_{nom}	nominal section strength
τ_{max}	maximum traction
a	crack length
a_0	initial crack length
D_{O_2}, D_{DOC}, D_{AO}	diffusion coefficients
$E, C, n, \beta, \gamma, d_{1,2,3}, X_0, v$	viscoplastic model constants
F_{max}	maximum load
G_{Ic}	fracture energy
H	specimen height
W	specimen width
K	stress intensity factor
k	rate constants for chemical kinetics model
L	ligament length
m, n	model constants
M_c	threshold molecular weight
M_w	weight average molecular weight
T	specimen thickness
t	time
T_g	glass transition temperature
W	specimen width
X	hardening state variable
x	spatial coordinate
AO	anti-oxidant
CCG	creep crack growth
CZM	cohesive zone model
DEN	double edge notch
DOC	chlorine dioxide
FEA	finite element analysis
HDPE	high density polyethylene
HE	hydrogen embrittlement
PE	polyethylene
PMMA	poly(methyl methacrylate)
SCC	stress corrosion cracking

cracking (SCC). Therefore, understanding the interaction between chemical degradation and fracture behavior for SCC is crucial for the design of polymer structural components for a target lifetime requirement.

Over the past few decades, both experimental and numerical studies have been performed to investigate creep crack growth (CCG) and SCC of polymers. Due to the long service time of polymer components, SCC experiments are usually accelerated by elevating the test temperature and increasing reactant concentration. Lu and Brown [23] conducted extensive tests to study the failure time due to creep of a polyethylene copolymer. Specimens were tested at high temperatures (up to 80 °C) and different stress levels. Then, time–temperature superposition was used to extrapolate the lifetime–stress relation at room temperature from the higher temperature experiment results. Hsuan et al. [16] developed a Notched Constant Tensile Load test to evaluate the stress corrosion resistance of high density polyethylene (HDPE) geomembranes. In this test, single edge notched dogbone specimens were immersed in a highly corrosive environment (10% Igepal) at an elevated temperature when constant tensile stresses were applied. The ultimate specimen failure time, as well as the applied stress, revealed the resistance of the tested resin to SCC.

The accelerated testing method is a valuable tool to measure the polymer performance under CCG and SCC, at least on a comparative basis. For instance, pipe manufacturers can use this approach to select the best performing material among