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Impact of material and physical parameters of the crack layer theory on slow crack growth behavior of high density polyethylene

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ABSTRACT

The crack layer theory, proposed by A. Chudnovsky many years ago, can be a very effective tool to quantitatively model slow crack growth in engineering thermoplastics. However, the large number of input parameters required by this theory has been a technical hurdle for its use in industrial and research applications. Thus, in order to achieve a practical applicability of the crack layer theory, a clear understanding of the effect of each parameter on slow crack growth is quite important. In this study, simulations of slow crack growth in high density polyethylene are performed using the crack layer theory for various key parameters, and the effect of each parameter on crack growth behavior in high density polyethylene is investigated.

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1. Introduction

For the lifetime prediction of long-term failure in engineering thermoplastics, which is a main failure mode in structural applications of thermoplastics, a large effort has been devoted to the development of slow crack growth (SCG) models and the linkage between accelerated testing and field failure. Engineering thermoplastics usually show different failure modes depending on the applied load and environmental conditions [1,2]. Under high load, most engineering thermoplastics fail in a short time by ductile failure. In the case of intermediate load levels, it is commonly observed that engineering thermoplastics fail in a quasi-brittle manner with significant SCG, and many unexpected field failures of load-bearing engineering thermoplastics are related to this mode of failure [1,2]. Moreover, reactive chemicals surrounding the engineering thermoplastics also affect the lifetime of the material, leading to relatively long lifetimes with failure modes of environmental stress cracking or stress corrosion cracking depending on the chemical and/or physical damage of the material [3,4].

Therefore, the prediction of the lifetime to failure, in the case of quasi-brittle fracture, and the development of accelerated tests to predict field failures is very important. Simple extrapolations of experimental data without proper justification must be avoided due to transitions of the SCG mechanism and kinetic over time [2,5,6]. In general, empirical models such as Paris' equation have limited applicability to polymers due to the complexity of crack growth characteristics in engineering thermoplastics. In particular, the discontinuous crack growth behavior under both creep and fatigue loading conditions has been widely observed in brittle fracture of engineering thermoplastics [7–12]. Such crack growth behavior cannot be simulated by conventional models. A more general model such as the crack layer (CL) theory proposed by A. Chudnovsky in [13,14], is required in order to capture the complexity of cracks and the surrounding damage zone interaction resulting in continuous,

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Nomenclature

A, m	coefficients of the relation between slow crack growth rate and stress intensity factor
E'	plane strain elastic modulus
G	Gibbs potential
J_1^{PZ}, J_1^{CR}	elastic energy release rate at process zone and crack tips
k_{CR}, k_{PZ}	kinematic coefficients of crack and process zone growths
K_I	stress intensity factor
K_{Ic}	critical stress intensity factor
l_{pz}, l_{CR}	length of a process zone and a crack
t_i	elapsed time for the transformation from fresh material into process zone material
t_f	time to failure
t^*	characteristic time for degradation
X^{PZ}, X^{CR}	driving forces for a process zone and a crack
γ	specific fracture energy
γ_0	initial SFE of fresh material
γ^{tr}	transformation energy per unit volume
δ_{tot}	crack opening displacement at the crack tip
λ	natural draw ratio
σ_∞	remote stress
σ_{dr}	drawing stress

discontinuous, and mixed mode crack growth [2]. The crack layer theory considers the crack and its surrounding damage zone (commonly called "process zone") as a single entity (crack layer) with a few degrees of freedom, and makes use of thermodynamic considerations for modeling the CL evolution. In order to understand the SCG behavior of engineering thermoplastics in the most general manner, a crack and the damage zone around the crack may be considered as a single entity and applied in SCG simulations of engineering thermoplastics [13].

The CL theory can be used to simulate the different SCG modes of engineering thermoplastics, i.e., continuous, discontinuous, or the transition between these two modes [13–17]. According to [13], the CL is a system of a main crack with its surrounding damage zone, also known as the process zone (PZ). In the CL theory, the thermodynamic interaction between the main crack and different surrounding damaged areas is established, considering the energy dissipation required to generate micro-cracks or micro-damages. The applicability of the CL theory has been convincingly demonstrated in various thermoplastics such as high density polyethylene (HDPE), polystyrene, and polycarbonate, which show dissimilar damage structures [13–19]. In other words, the CL theory has the potential to connect the morphological structures with the crack and damage zone growth in a general way. From the fact that the CL simulation provides not only the lifetime or SCG rate but also elucidates the entire crack and damage zone growth process; it has a great potential to be employed in industrial settings, replacing the conventional empirical models. Despite the many scientific benefits of the CL theory, there are several problems to be solved regarding the application of the CL theory in the simulation of the SCG behavior of engineering thermoplastics. In the CL theory, two coupled driving-force equations, which are related to the crack and PZ growth respectively, are derived from nonlinear differential equations. Consequently, the driving forces should be solvable by numerical methods [1,17]. In particular, the diverse input parameters such as the initial specific fracture energy (SFE), transformation energy, characteristic time for material degradation, and so on, make the use of the CL theory quite complicated.

Actually, most studies on the CL theory have concentrated on the reproduction of specific test results provided by CL simulations with limited input parameters [18,19]. An understanding of how each parameter affects the overall CL growth process must be established so as to efficiently apply the CL theory to diverse practical cases. In this study, to address the above technical issues, a detailed parametric study with a variety of input parameters of the CL theory for HDPE was performed on single-edge-notched (SEN) specimens in creep conditions. The effect of each input parameter on the CL growth, i.e. the growth of the crack and the PZ, is elaborated. To quantitatively investigate the effect of each parameter of the CL growth, the conventional relationship between the SCG rate and the stress intensity factor is constructed and compared. Based on the constructed relationship, the time to failure of HDPE under discontinuous SCG is predicted for various input parameters. In addition, the detailed backgrounds of the CL theory and a CL simulation algorithm are also introduced.

2. Application of the crack layer theory to high density polyethylene

2.1. Overview of the crack layer theory

Detailed observations of the fracture propagation process in HDPE are required in order to understand the SCG behavior and link it to the mechanisms and kinetics of crack growth. In HDPE, the PZ is always present in front of a crack and a strong crack-PZ interaction affecting the SCG should be explicitly addressed.

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