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On the opening profile and near tip fields of an interface crack between a polymeric hydrogel and a rigid substrate

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ABSTRACT

The opening profile and near tip stress fields of an interface crack between a polymeric hydrogel and a rigid substrate in the plane strain case are studied with the finite element method. The constitutive model proposed by Hong et al. (2008) is implemented by using a user subroutine in ABAQUS to simulate the chemo-mechanical coupling behavior of the hydrogel. Two interface models in front of the crack tip are considered, i.e., a perfectly bonded interface (fully pinned) model and a cohesive interface model. Our numerical results show that, when subjected to a tensile load, the solvent molecules in the hydrogel tend to concentrate around the crack tip and introduce extra swelling, which influences the opening profile and near-tip fields of the interface crack. For the fully pinned interface model, an increase of the free swelling stretch may hinder the flipping over of the crack face. The dominant stress component in front of the crack tip is closely related to the opening profile of the interface crack. The effect of interface damage on the opening profile of the interface crack is also studied in this paper with the aid of the cohesive zone model. Our study indicates that the intrinsic properties of the interface have significant influences on the opening profile of the interface crack.

1. Introduction

Hydrogels are crosslinked polymer chains with solvent molecules (e.g., water). The response of hydrogels to external forces or chemical stimuli involves deformation coupled with solvent diffusion and is a chemo-mechanical coupling process [1]. Due to their biodegradability and mechanical and chemical compatibility with natural tissues, hydrogels are believed to be the future materials for tissue scaffolding and replacement [2]. Common synthetic hydrogels are usually very soft and brittle and cannot withstand large deformations. However, recent years have witnessed the fast development of both strong and tough hydrogels [3–9]. Gong et al. [3] firstly discovered that hydrogels can achieve high toughness by using double networks. Permanent damages are present in the internal network when the hydrogel is subjected to large deformations. Therefore, the mechanical properties of double network hydrogels are usually severely degraded in the following loading cycles. To resolve this problem, some researchers have suggested replacing the covalent bonds of the brittle network with

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Nomenclature

F_{iK}	deformation gradient tensor
$\mathbf{X}$	position vector of the material particle in the reference configuration
$\mathbf{x}$	position vector of the material particle in the deformed configuration
μ	chemical potential
$\hat{W}(\mathbf{F}, \mu)$	free energy density
N	number of polymer chains per unit volume in the reference state
$\mathbf{s}$	nominal stress tensor
$\boldsymbol{\sigma}$	true stress tensor
J	the first invariant of the deformation gradient tensor
I	the second invariant of the deformation gradient tensor
$\mathbf{H}$	transpose of the inverse of the deformation gradient tensor
kT	temperature in the unit of energy
v	specific volume of the solvent molecule
χ	dimensionless parameter characterizing the enthalpy of mixing
λ_0	free swelling stretch
λ	applied stretch
C	concentration of the solvent molecule
a	crack length
l	dimension of the square shaped hydrogel specimen
$\sigma_n,\ \tau_s,\ \tau_t$	cohesive stresses of the tensile, shear and tearing mode
$\delta_n,\ \delta_s,\ \delta_t$	crack opening displacements of the tensile, shear and tearing mode
$\sigma^N,\ \tau^S,\ \tau^T$	peak cohesive stresses of the tensile, shear and tearing mode
$\delta_n^F,\ \delta_s^F,\ \delta_t^F$	failure displacements of the tensile, shear and tearing mode
$G_{\mathrm{IC}},\ G_{\mathrm{IIC}},\ G_{\mathrm{IIIC}}$	fracture toughness of the tensile, shear and tearing mode

non-covalent bonds to allow the recovery of the fractured bond [4–9]. Following this idea, strong and tough hydrogels with high deformability and self healing characteristics have been successfully synthesized in laboratories [4–9].

Though intensive efforts have been devoted to the synthesis of high performance hydrogels, research work on the fracture behavior of hydrogels is relatively much less found in the open literature. To name a few, Baumberger et al. [10] and Seitz et al. [11] studied the role of solvent on crack propagation dynamics in hydrogels. Tanaka et al. [12] found that there exists localized yielding around crack tips of double-network gels. Brown [13] proposed a simple model to interpret the high toughness of double network gels. Tanaka [14] studied the rate effect in the fracture of rubbers and chemically cross-linked gels with a molecular theory. Baumberger and Ronsin [15] studied the Mode I crack dynamics in gelatin gels with experiments. Kundu and Crosby [16] studied the cavitation and fracture behavior of polyacrylamide hydrogels with experiments and scaling theories. Zhang et al. [17] found that swelling induced by the solvent may induce crack healing in gels. Wang and Hong [18] investigated the delayed fracture in gels with a continuum visco-poroelastic model. Most recently, Zhang et al. [19] developed a coupled cohesive-zone and Mullins-effect model to predict the fracture energy of soft tough materials under large deformation. Though important insights have been gained to understand the fracture behavior of hydrogels from these studies, it still remains to be a difficult task to precisely characterize the crack tip fields in hydrogels [20]. Considering that there exist various energy dissipation mechanisms in the newly synthesized tough hydrogels, it is also of great importance to develop a model to characterize the fracture toughness of these hydrogels, especially when the rate effect is involved, which help to develop new tough hydrogels and is also important for the practical applications of these hydrogels in important fields like tissue scaffolding and replacement.

It has been shown by Hui et al. [21] that unlike cracks in hard materials, cracks in soft elastomers display a blunted shape. The asymptotic deformation and stress fields near the tip of a crack in soft elastic solids are summarized by Long and Hui [20] recently. These solutions are based on finite strain elastostatics and hyperelastic material models, and exhibit different characteristics compared with the classical crack tip fields in linear elastic fracture mechanics. The finite strain stress fields near the tip of an interface crack between a soft incompressible elastic material and a rigid substrate are studied by Krishnan and Hui using the finite element method [22]. They found that, for a pinned interface crack under plane strain deformation, the true opening normal stress is found to be lower than the shear stress and the transverse normal stress. The crack face flips over and the tip angle is almost tangential to the interface. Their study also implies that interface friction can play a very important role in the near tips fields of an interface crack between a soft material and a rigid substrate. In another paper, Lengyel et al. [23] studied the influences of interfacial slippage and material compressibility on the deformation and stress fields near the tip of a plane interface crack between a compressible hyperelastic material and a rigid substrate. They found that both the interfacial slippage and material compressibility can influence the deformation and stress fields. It is noted that