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Predicting fracture energies and crack-tip fields of soft tough materials

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ABSTRACT

Soft materials including elastomers and gels are pervasive in biological systems and technological applications. Whereas it is known that intrinsic fracture energies of soft materials are relatively low, how the intrinsic fracture energy cooperates with mechanical dissipation in process zone to give high fracture toughness of soft materials is not well understood. In addition, it is still challenging to predict fracture energies and crack-tip strain fields of soft tough materials. Here, we report a scaling theory that accounts for synergistic effects of intrinsic fracture energies and dissipation on the toughening of soft materials. We then develop a coupled cohesive-zone and Mullins-effect model capable of quantitatively predicting fracture energies of soft tough materials and strain fields around crack tips in soft materials under large deformation. The theory and model are quantitatively validated by experiments on fracture of soft tough materials under large deformations. We further provide a general toughening diagram that can guide the design of new soft tough materials.

1. Introduction

Except bones and teeth, most parts of animal bodies consist of soft materials—elastomers and hydrogels with relatively low rigidity and high deformability compared to hard materials such as steel and ceramics. Biological soft materials such as cartilage, muscle, skin and tendon usually need to maintain high toughness, which is critical for survival and well-being of animals under various internal and external loads [1]. Soft materials also promise broad technological applications in areas as diverse as soft machines and robots [2–4], artificial tissues and organs [5], non-conventional electronics [6,7], and microfluidics and optics [8,9]. In these applications, high toughness of the materials is usually required for reliability and robust function of the systems.

Owing to their scientific and technological importance, various soft tough materials have been developed in recent decades [10–13]. The intrinsic fracture energy of soft materials – i.e., the energy required to fracture a layer of polymer chains in front of the crack [14] – is relatively low; and it is qualitatively known that the toughening of soft materials generally relies on mechanical dissipation in process zones around cracks [14–20]. However, it is still not well understood how the intrinsic fracture energy and mechanical dissipation cooperate synergistically to give rise to high fracture toughness of soft materials [21]. Furthermore, physical models that can predict the fracture energy and crack-tip strain fields of soft materials are of imminent importance to the design of new soft tough materials, but such predictive models still do not exist.

Here, we report a scaling law and a continuum model that quantitatively accounts for the synergistic contribu-

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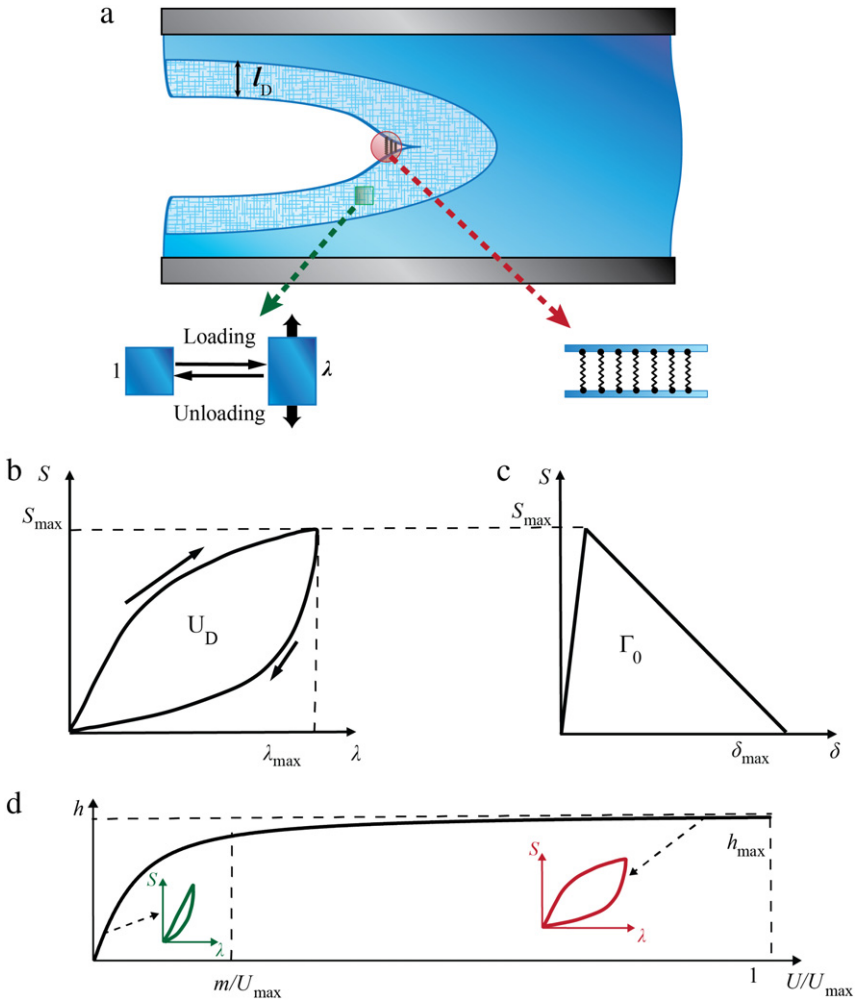

Fig. 1. Schematics of the theory and model for fracture in soft tough materials. (a) Crack propagation in a soft tough material under pure-shear test. A process zone with height l_D develops in the material during crack propagation. (b) The mechanical dissipation in the process zone is characterized by the Mullins effect. A typical stress–stretch curve of the soft material under cyclic pure-shear tensile deformation. The hysteresis loop in the curve indicates mechanical dissipation. (c) The intrinsic fracture energy of the soft material is characterized as a cohesive-zone model with triangle traction–separation law. (d) The hysteresis ratio of the soft material monotonically increases with the maximum work done to the material.

tions of intrinsic fracture energies and dissipations to the total fracture energies of soft materials. We characterize the essential physical features of intrinsic fracture energy and dissipation using the cohesive-zone model and Mullins-effect model, respectively, implemented in finite-element software, ABAQUS. Our calculation shows that the total fracture energy of soft material scales linearly with its intrinsic fracture energy, while the effect of dissipation manifests as a scaling pre-factor that can be much higher than one. To validate the theory and model, we measure the stress–strain hysteresis and intrinsic fracture energies of polyacrylamide-alginate (PAAm-alginate) hydrogels of different compositions, which represent soft tough materials with different properties [12,22]. Using the material parameters measured independently, our model can quantitatively predict the fracture energies of different soft materials as well as strain fields and crack propagations in them. Based on the model, we further calculate a toughening diagram that can guide the design of new soft tough materials.

2. Scaling analysis

Let us consider a notched soft material undergoing the pure-shear test to measure its fracture energy, as illustrated in Fig. 1(a) [23]. Crack propagation in the soft material requires the scission of at least a layer of polymer chains. The required mechanical energy for chain scission divided by the area of crack surface at undeformed state gives the intrinsic fracture energy, Γ_0. In addition, material elements in a process zone around the crack will also be deformed and undeformed as the crack propagates. If mechanical energy is dissipated during this process, the dissipated energy divided by the area of crack surface at undeformed state further contributes to the total fracture energy by, Γ_D (Fig. 1(b)). Therefore, the total fracture energy of a soft material can be expressed as

$$\Gamma = \Gamma_0 + \Gamma_D \tag{1}$$

where $\Gamma_D = \bar{U}_D l_D$ and $\bar{U}_D$ is the mechanical energy dissipated per the volume of the process zone, and l_D the