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A novel essential work of fracture experimental methodology for highly dissipative materials

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ABSTRACT

Determining fracture toughness for soft, highly dissipative, solids has been a challenge for several decades. Amongst the limited experimental options for such materials is the essential work of fracture (EWF) method. However, EWF data are known to be strongly influenced by specimen size and test speed. In contrast to time-consuming imaging techniques that have been suggested to address such issues, a simple and reproducible method is proposed. The method accounts for diffuse dissipation in the specimen while ensuring consistent strain rates by scaling both the sample size and testing speed with ligament length. We compare this new method to current practice for two polymers: a starch based food and a polyethylene (PE) tape. Our new method gives a size independent and more conservative fracture toughness. It provides key-data, essential in numerical models of the evolution of structure breakdown in soft solids as seen for example during oral processing of foods.

1. Introduction

Natural and synthetic polymers are ubiquitous in everyday life [1]. Research into their deformation and fracture mechanisms has been an ongoing topic for several decades concerning scientists from diverse backgrounds and disciplines including Mechanical Engineering [2,3], Chemistry [4,5], Biology [6,7] and Medicine [8,9]. Amongst their numerous applications, the food sector has recently received much attention [7,10]. Humans breakdown their food to reduce the intake into smaller pieces suitable for swallowing and digestion [7,8,11]. This oral process and the associated sensory perception largely depends on both the food raw ingredients used and the processing parameters employed during production [12,13]. Features affecting texture and palatability can be described using mechanical properties—amongst them fracture toughness [7,12], which describes the energy required to create new surfaces, as experienced during chewing. Therefore fracture toughness data are desirable, not at least as a key input parameter in mastication Finite Element models for predicting sensory related attributes [12,14,15], such as chewing force [7] and breakdown speed [10]. Various numerical methods for modelling fracture, such a cohesive traction separation law [15–19] and the element stiffness degradation framework [10,14], are based on energy consumption strictly in the process zone at the vicinity of the crack tip [20], such that the true fracture toughness parameter is required for accurate simulations [10].

Concerns over the fracture characteristics of polymers also extend to film applications such as paint coatings [21,22] and adhesive tapes [23,24]. The latter is investigated in this study in addition to a food product. Adhesive tapes involve pressure-sensitive adhesives (PSA) supported on thin film polymeric substrates. Example applications include labels, packaging tapes [19], transdermal patches [18] and surgical skin adhesives [23]. Consequently, there is an increasing need to understand and optimise not only the interfacial (peeling) behaviour, but also the film's fracture properties. Convenient tests for determining fracture toughness values serve either in product development through correlations to molecular structure or mass [23,25], or in establishing engineering limits for a given application.

The fracture characteristics of soft solid polymers are nevertheless often difficult to obtain [10,16]. Both the food and the adhesion tape examples mentioned above do not obey the Linear Elastic Fracture Mechanics (LEFM) assumptions and thus the corresponding established test methods are rendered invalid [2,10,26].

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This is due to their strong time dependence, high compliance, and other dissipative phenomena such as stress softening [10]. These attributes contribute to the complexity surrounding the calculation of the stored energy available for crack propagation [2,10,27]. Test methodologies established in literature so far include the "trouser tear" test for soft bio-materials [28], wire cutting in cheese [17] and gelatine gels [16] and recently orthogonal cutting [29,30], which was "borrowed" from work on metals [31] and lately applied to polymers [27] and other soft solids [10,32].

Post Yielding Fracture Mechanics (PYFM) theory is seen as a viable alternative to LEFM for such materials as it describes fracture through material that has already yielded [33–35]. The Essential Work of Fracture (EWF) method has proven popular in particular as it results in a single, fundamental parameter to describe stable crack growth [36,37]. Initially developed as an alternative to "J integral" tests [38,39] due to the difficulty in performing the latter owing to severe blunting during crack growth, the method is simple in that it separates the total energy distinctly into that used for fracture, and for other dissipative processes nonessential to fracture [36]. While originally used to obtain the plane stress fracture toughness of thin sheets, recent work has extended the method to thicker specimens (plane strain) [40–43] as well as viscoelastic materials [10,44].

However, the EWF method has not yet led to a published test standard [36,45], as round-robin tests have highlighted the effect of factors such as specimen size [10,46,47], thickness [41,48,49], speed [50,51] and notching procedure [36,52,53] on the derived data, although the notching problem is a common concern across much of polymer testing [54]. Concerns have also been reported [27,44] regarding the potential variation in the stress state local to the crack tip affecting the fracture process when different ligament lengths are used (see section 2 for a description of the classic EWF method). Specifically Rink et al. [38] demonstrated that a true toughness value at crack initiation may be determined only when full yielding occurs in all the ligament lengths. More importantly, the EWF method as it currently exists does not adequately account for the contribution of the specimen arms (denoted as region V_e, in Fig. 1) to the total energy [34,36]. It assumes that energy is dissipated only within a limited region, V_p, (see Fig. 1), local to the yielded ligament. This led to various corrections being proposed [34,44,47]. The recommendation is that using a gauge length, g, equal to the ligament length, l (see Fig. 1(c)), to measure the energy input gives more accurate results [38,47] as opposed to measuring the deflection across the whole specimen length, L, [10]. Drozdov et al. [33] quantified the inelastic energy dissipated remotely and subtracted the amount from the total energy to derive the energy essential to fracture. Recently, Hossain et al. [23] used the in- situ digital image correlation (DIC) technique to obtain full-field 2D strain distributions in the specimen and directly partition the total energy. In both of the latter two studies [34,44], independent tensile tests were necessary in evaluating the constitutive strain energy density associated with uniaxial deformation, and Hossain et al. acknowledged that an error is likely in these calculations since the stress state near the crack tip is multi-axial. Apart from the inability of DIC to track very high strain levels [34,55], it is further argued here that such techniques may be further complicated in rate dependent polymers, which display rate dependent stress-strain curves. To summarise, current efforts to compensate for viscoelastic effects require optical, (e.g. DIC), or extensometer measurements (for gauge deflections), which can be time and cost inefficient, as well as difficult to reproduce in different labs. Finally, no study so far has considered the potential error due to the inconsistent true strain rates being applied when the ligament length is varied.

This work addresses these issues by proposing a novel modification to the EWF method so that it can account for diffuse dissipation throughout the effective specimen volume, whilst vanishing the need for correction methods such as the independent measurement of the gauge length deflection. As will be discussed, the new method ensures a common crack tip deformation state and it also corrects the inconsistency which arises when strain rates vary with the ligament length. The proposed method is validated using a starch based food product, known for its strong rate dependence and dissipative behaviour [10], as well as on a polyethylene (PE) film, with a well characterised time-dependent behaviour and high extensibility [56,57] which magnifies the remote dissipation effects and the associated error. Starch is largely used by the food industry and the need for a robust test that determines its fracture characteristics is ever increasing [10]. PE film is commonly utilized in packaging applications as well as in adhesive tape products where it is used as the substrate for pressure sensitive adhesives [18].

The outline of the paper is as follows. Firstly, a detailed analysis of the classic EWF test along with the novel EWF approach is provided, followed by the description of the materials used and the experimental procedures adopted. Thereafter, the experimental results are presented and the two methods are compared. Finally, the merits of the novel EWF approach are discussed.

2. Background

2.1. Classic EWF method

The EWF test analysis provides a fundamental material property, the specific essential work of fracture, w_e, also known as the fracture toughness, which is the energy per unit area required to create new crack faces. This energy is essentially dissipated locally at the process zone surrounding the crack tip [36]. The method uses the Double Edge Notched tension (DENT) geometry shown in Fig. 1. Upon loading, it is assumed that the system can be partitioned into three distinct regions that dissipate energy: the ligament section, A_f, a plastic zone surrounding the ligament, V_p, and the remaining part of the specimen, V_e [34]. The ligament area is the fracture process zone where the essential work of fracture, W_e, is dissipated to form the fracture surfaces [36]. The plastic zone, V_p, is the volume that consumes the non-essential energy, W_p, due to plastic deformation [37] or other dissipative mechanisms [21]. Importantly, the remaining part of the body, V_e, is assumed to deform elastically, such that it reverses its stored energy during tearing [36]. The EWF method postulates that the essential work of fracture is the dissipation per unit fractured area on average over the entire crack propagation in the ligament, such that the following two assumptions are made:

a) W_e is proportional to the ligament area, such that the specific parameter, w_e, is introduced as shown below:

$$W_e = w_e B l \tag{1}$$

Note that, w_e, has units of kJ/m^2 and is the true fracture toughness of the material to be determined from the tests, and

b) W_p is proportional to the volume of the plastic zone, V_p, and the shape factor, β, is used to give:

$$W_p = w_p \beta B l^2 \tag{2}$$

where, B, is the sample thickness (out of plane sample dimension in Fig. 1), l, the ligament length, β, the plastic zone shape factor and the parameters w_e and w_p indicate the energy consumed per unit