



Material properties

The effect of temperature on the tearing of rubber

Kartpan Sakulkaew^{a,b}, Alan G. Thomas^a, James J.C. Busfield^{a,*}^a Department of Materials, Queen Mary, University of London, Mile End Road, London E1 4NS, UK^b Department of Science Service, Rama VI Road, Bangkok 10400, Thailand

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ABSTRACT

The tearing behaviour of rubber is typically characterised using an energy balance approach where the rubber has a geometrically independent relationship between the crack growth rate and the strain energy release rate. This approach works well during steady tearing, such as that encountered with an unfilled, non-strain crystallising rubber such as styrene butadiene rubber. The rate of tearing is both easy to measure experimentally and to then interpret. However, this approach is made more complicated under conditions where the rubber exhibits unsteady crack growth such as stick slip tearing or knotty tearing, which is often encountered with a strain crystallising rubber such as natural rubber or when reinforcing fillers are used. Under these conditions it is not easy to measure the crack growth rate as the value adopted is usually the average of a very rapid tearing rate and a zero velocity tearing rate. The approach adopted in this study characterises the rate of increase in the strain energy with time, \dot{T} , at the crack tip just before the onset of tearing. The relation between this and the critical strain energy release rate T^* for the crack propagation is examined over a wide range of tear rates and temperatures for several different rubber materials, including natural rubber (NR), epoxidized natural rubber with half of the isoprene units being epoxidized (ENR-50) and polybutadiene rubber (BR). It is apparent that the critical strain energy release rate, T^* is surprisingly independent of the rate of strain at the crack tip for the majority of materials and over a wide range of temperatures. Only when tearing has become very rapid do additional viscoelastic mechanisms result in significant toughening of the rubbers.

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1. Introduction

Tearing behaviour of rubbers has been extensively investigated in terms of the relationship between the strain energy release rate, which is often referred to as the tearing energy, and the tearing rate [1–4]. The strain energy release rate of a material, T , is the change in the elastic strain energy per unit change in crack surface area. It is defined in the form:

$$T = -\frac{1}{h} \left(\frac{\partial W}{\partial c} \right)_l \quad (1)$$

where W is the total elastic strain energy stored in a specimen of thickness h measured in the unstrained state and c is the crack length. The suffix l denotes that the constrained boundaries of the body do not move and so no external work is done during the propagation of the crack. A value of T can be applied to the specimen containing an incision and the rate of crack growth can be measured experimentally. In the trouser tear test specimen, as shown in Fig. 1, the tearing behaviour of rubber can be primarily classified into two main types: steady or unsteady (sometimes known as stick-slip) [5]. During this test the boundaries move, therefore, the strain energy release rate per unit area of crack growth, T , must also now include an additional term to account for work done associated with the movement of the boundaries during tearing. The resulting expression for the strain energy release rate being given as

* Corresponding author. Tel.: +44 (0) 20 7882 8866.

E-mail address: j.busfield@qmul.ac.uk (J.J.C. Busfield).

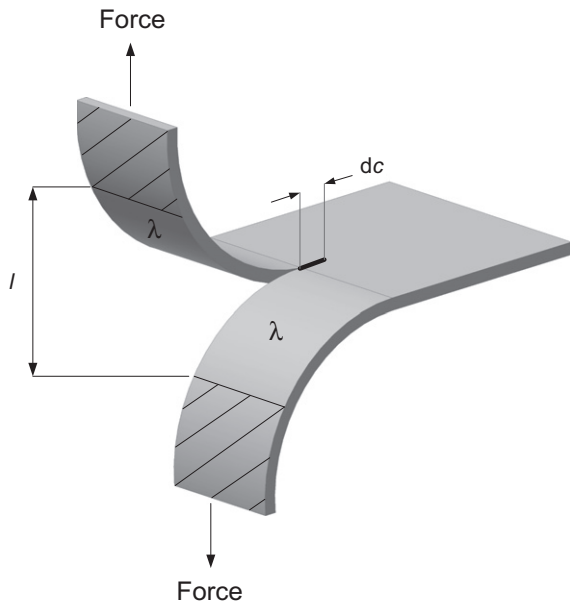


Fig. 1. Trouser specimen (the hatched line represents the area being clamped by the grips of the test machine).

$$T = \frac{2F\lambda}{h} - bW \quad (2)$$

where F is the applied tearing force, h is the specimen thickness, λ is the extension ratio in the legs, b is the total width of the specimen and W is the elastic stored energy in the legs of the specimen far removed from the crack tip. W is determined from an integration of a stress-strain curve at a strain that corresponds to the extension ratio in the legs of the specimen at the point of tearing. Generally, the relationship between the tearing rate and the strain energy release rate is a material characteristic that is independent of the test piece geometry [5,6].

In the trouser tear test piece, the tearing at the crack tip is generated by a critical release of elastically stored strain energy in the legs, which are essentially in uniaxial extension at a corresponding extension ratio, λ . Referring to Fig. 1, if the crack length increases by dc , the separation l of the clamps is increased by

$$dl = 2\lambda dc \quad (3)$$

In the case of smooth and continuous tearing, the average crack growth rate can be determined from the rate of separation of the clamps, S , by the relation

$$S = \frac{dl}{dt} = \frac{2\lambda dc}{dt} \quad (4)$$

where l is the separation of the clamps of the test machine, t is time and c is the crack length. This approach can be used correctly to characterise the tearing of rubber when the rate is steady, as is often observed with an unfilled and non-crystallising rubber such as styrene-butadiene rubber (SBR). During steady tearing, the rate of propagation essentially remains constant once tearing has commenced. However, for a lot of rubber materials such as strain-

crystallising rubbers like NR and BR, or for rubbers filled with reinforcing fillers such as carbon black, the rate of tearing is no longer steady. The resulting unsteady tearing behaviour can be either stick slip in nature, as shown in Fig. 2(a), or even knotty in behaviour, as shown in Fig. 2(b). Under these unsteady crack growth conditions an average rate of crack growth calculated from the cross head displacement rate is meaningless, as it is just an arbitrary average of an unspecified rapid rate of crack growth and a zero rate.

A much more useful measure of the tearing rate would be the rate of increase in strain at the crack tip immediately prior to tearing [7], which can then be related to the critical strain energy release rate for the material. It has been shown that the strain energy release rate is approximately a product of the diameter of the tip referred in the unstrained state, d , and the strain energy density, E , integrated around the crack at break [8]. It is given by the relation.

$$T \approx dE \quad (5)$$

It is assumed that the characteristic crack tip diameter, d , does not significantly change during tearing, and thus a measure of the strain energy release rate is proportional to the strain energy at the tip of the crack. It is possible to take the time derivative of Equation (5) to develop the following relationship,

$$\dot{T} \approx d\dot{E} \quad (6)$$

Therefore, \dot{T} (dT/dt) is the rate of change in the strain energy release rate with time which is proportional to, \dot{E} (dE/dt), the rate of change of the strain energy with time at the tip of the crack. Similarly, the rate of strain energy increase at the crack tip can be considered to be a simple relationship with the rate of strain at the crack tip. This equation shows that a measure of the rate of change of strain energy release rate with time can be utilised as an equivalent measure of the increase in strain at the crack tip with time.

In this study, three unfilled strain-crystallising rubbers which exhibit unsteady tearing behaviour were investigated. Three different base polymers with significantly different glass transition temperatures as shown in Table 1 have been utilised: natural rubber, NR (SMR CV60), epoxidized natural rubber with half of the isoprene units being epoxidized (ENR-50), and polybutadiene rubber, BR (JSR BR01) with a 95% *cis* content. All these rubber materials were supplied by the Tun Abdul Razak Research Centre (TARRC), UK. The materials were crosslinked with sulphur to various degrees of crosslinking with the ratio of the accelerator to sulphur set at 0.3.

2. Experiment

The rubber formulations are given in Table 1. The compounded rubbers were prepared using a two-roll laboratory mill in accordance with ISO 2393. The cure characteristics of the materials were determined at 150 °C with a curemeter (Monsanto MDR 2000) according to ISO 6502. The samples were then cured in a hydraulic hot press

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