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The deformation and fracture of balloons

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ABSTRACT

Inflation of balloons provides a straightforward way of achieving large biaxial deformations. Previous studies have shown that when a balloon bursts, crack propagation occurs at very high speed – much higher than would be expected from the low strain modulus and elastic wave velocity of the rubber. The present paper is concerned with studies of the deformation and fracture of cylindrical balloons. On inflation, the deformations of such a balloon pass through an unstable region but subsequently increase monotonically with pressure. In this relatively high pressure region, the ratio of the longitudinal and circumferential extension ratios is broadly in accord with expectations from high-strain elasticity theory when the ratio of the corresponding stresses is taken into account. On bursting, crack speeds up to around 300 m/s in this region. It is shown that these speeds are in accord with large increase in incremental moduli for the highly-strained rubber. Marked changes in crack tip profile observed at very high crack speeds are consistent with control of the rate of growth by inertia rather than by the viscoelastic properties of the rubber (as is believed to be the case at lower speeds). Consistent with this, various elastomers having different glass transition temperatures show similar crack growth behaviour in the very high speed region.

1. Introduction

In an earlier paper [1], it was shown that in simple extension or pure shear, the rate of crack propagation in a vulcanized elastomer appeared to approach a limiting value at high elastic energy release rates. The magnitude of the limiting value is around 30 m/s which is of the order of the shear wave velocity expected from the low strain modulus of the material. In this region, the influence of parameters such as crosslink type, crosslink density, glass transition temperature or fillers is essentially the same as at much lower crack speeds and energies. Thus, although the fracture surfaces are often quite smooth (and apparently glassy), the material behaviour appears to remain essentially rubbery in nature in this high-speed fracture region [2]. The only difference from behaviour at much lower crack speeds is that effects normally associated with strain-induced crystallization are absent in the high-speed region – evidently the crack propagation is too fast for effective crystallization to take place at the crack tip.

Under large biaxial deformations, crack speeds up an order of magnitude higher than those referred to above are observed [3]. The present paper describes experiments on various elastomers under such deformations, which were conveniently attained by inflating balloons. In this ultra high speed region, it is found that crack speeds are substantially independent of the glass transition temperature of the elastomer. The shape of the growing crack tip is also very different from that observed at lower crack speeds in the tensile and pure shear experiments. Possible reasons for these differences and for the attainment of such high speeds are discussed.

As the fracture behaviour is clearly dependent on the modulus and strains of the rubber, the mechanics of the deformation is also studied in detail.

2. Experimental procedure

A convenient way of achieving large biaxial deformations is by the inflation of a balloon. In an earlier study [3], crack speeds that developed following the bursting of spherical balloons were studied. Some early experiments during the present study were also carried out with spherical balloons but they were found to be rather inconvenient to use because the direction of crack propagation was uncontrolled and the distance over which cracks could be followed (and measured) was limited by the curvature of the surface in which they were growing. Subsequently, cylindrical balloons were adopted as they provided a well-defined direction of growth, because the circumferential stress was greater than the longitudinal value (by a factor of two), on a surface that was

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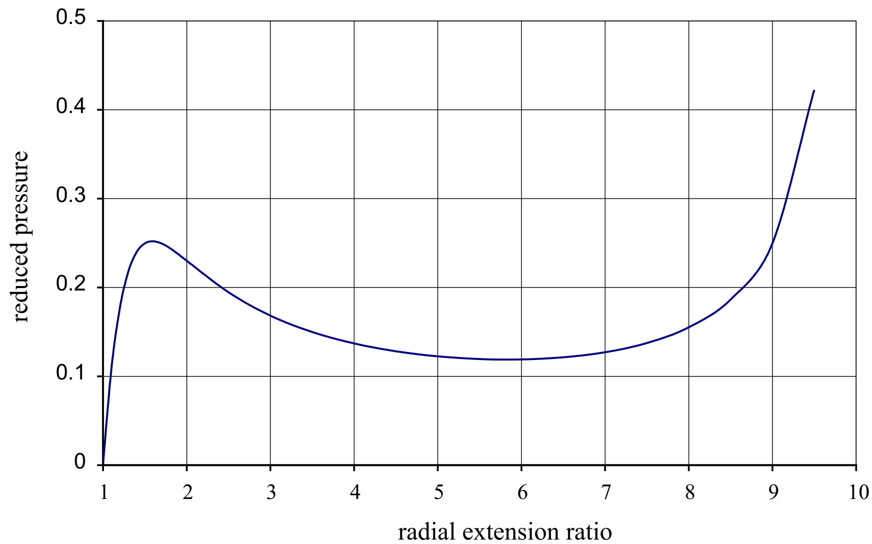

Fig. 1. Calculated pressure-radial extension ratio relation for a cylindrical balloon using the Gent strain-energy function [4]. The pressure P is presented as a reduced parameter Pa/h where a is the balloon radius and h the rubber thickness, both in the unstrained state.

essentially flat in the growth direction. Also, balloons up to a metre long in the inflated state were available, enabling correspondingly greater crack lengths to be used and thus greater accuracy to be attained in the velocity measurements. A limitation of the technique was that the process of inflation gave an unstable shape for moderate strains, a familiar phenomenon during inflation of cylindrical balloons, requiring that measurements be restricted to strains greater than about 500% where stability prevailed. This is not a severe limitation as in this paper we are concerned with very high-speed fracture where the strains are inevitably large. Fig. 1 shows the theoretical relation between the inflation pressure and the radial extension ratio for a cylindrical balloon, using the Gent strain energy function [4] with the parameters fitted to data of Treloar for natural rubber by Verron et al. [5]; this function models the higher strains adequately for the present qualitative purpose. The deformation will be discussed further later. The working range for the experiments is the region of positive slope at the higher pressures.

2.1. Materials

Commercial balloons made of natural rubber were used for most of the experiments, but in addition some balloons were specially made using natural rubber, butadiene–acrylonitrile or polychloroprene lattices by the Malaysian Rubber Producers Research Association (now the Tun Abdul Razak Research Centre), Hertford.

The formulations of the synthetic balloons, in parts by weight, were

Butadiene acrylonitrile: latex (Perbunan) 100, colloidal silica 1.5, zinc oxide 3.0, zinc dibutyldithiocarbamate 0.7, ZMBI 0.5, antioxidant (Wingstay H) 1.0, dried at 70 °C for 1 h and vulcanized at 110 °C for 30 min.

Polychloroprene: latex (Bayprene) 100, casein solution, 0.2, sulphur1.0, sodium dibutyldithiuramcarbamate 0.9, zinc oxide 5.0, tetraethylthiuramdisulphide 1.0,. antioxidant (Wingstay P) 1.0, dried at 70° for1 h and vulcanized at 120° for 1 h.

The specially-made natural rubber balloons were prepared from pre-vulcanized latex (Ruvultex), dried at 70 °C for 2 h.

Some commercial condoms of polyurethane and natural rubber were also used, so that a range of viscoelastic properties was covered.

Although all the samples were not strictly 'balloons', this term may be used generally to refer to them.

2.2. Fracture experiments

As with the earlier work [1], a high-speed video camera was used to monitor the growth of the cracks. For the present work, a rather faster camera than that used previously was available, (*ref*) providing framing rates up to 40,000 frames/s, although with a reduced screen height at the higher rates. In practice, the highest framing rate employed was 18,000 frames/s.

The camera recorded information digitally and continuously and could be triggered retrospectively immediately after a balloon had been burst, as was normally done. The relevant section was then recorded on a computer so that prints could be made of selected frames, which facilitated measurement of the crack position.

A balloon was inflated by compressed air that was passed through a tube upon which the balloon was mounted. The inflation pressure was measured close to the outlet from the balloon. The method by which this was done varied during the course of the experiments: initially, a commercial pressure gauge was used but subsequently this was replaced by a water manometer (the required pressures being quite small); in a third stage, the manometer was monitored continuously by a dedicated video camera, enabling the pressure at the moment of bursting of the balloon to be determined. The balloons showed considerable stress relaxation and creep, so that the pressure tended to vary continuously whether or not air was actually being admitted to the balloon.

2.3. Strain measurements

In order to enable the longitudinal and transverse extension ratios, and their variation with location, to be measured, a grid was marked on each balloon in the unstrained state. By measuring the separation of the grid lines initially and after inflation, the strains could be estimated. During early experiments, the distances were estimated by measuring with a rule. At this stage, the normal practice was to make a large number of measurements, thus providing a fairly comprehensive picture of the strains and their distribution. A disadvantage of this procedure was that the time