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FRACTURE MECHANICS OF RUBBER

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Abstract. *The fundamental principles of the application of fracture mechanics to rubber are briefly discussed. The importance of the problem arises because of the large nonlinear deformation of rubber which introduces difficulties in the solution of the boundary value problem of a cracked body made of rubber. The tear behavior of rubber can be conveniently described by the critical tearing energy which is a characteristic property of the material. The results of an experimental study of determining the crack growth behavior and critical tearing energies of pure tire rubber are presented. Constrained tension and trousers specimens were used for mode-I and mode-III loading, respectively. In the trousers specimens the force necessary to grow the crack varies widely from a maximum value at crack initiation to a minimum value at crack arrest. This result to a stick-slip stable crack propagation, that is, the crack arrest and reinitiates of fairly regular intervals. In the constrained tension tests crack initiation triggers catastrophic growth. Results for the critical tearing energies for mode-I and mode-III are given.*

1. INTRODUCTION

The problem of crack growth in elastomers was first studied by the monumental work of Rivlin and Thomas [11]. They extended the Griffith criterion for growth of a crack in brittle materials to the case of vulcanized rubber. The criterion for the onset of tearing involves a characteristic energy which is a material property independent of the type and geometry of the test piece. When the tearing energy, which is equivalent to the strain energy release rate in the Griffith criterion, exceeds the critical value crack growth occurs. The tearing energy is supplied either from the strain energy of the deformed rubber, or, as a work done by the applied forces, or both. Due to the insurmountable difficulties encountered in the solution of a large deformation finite elasticity problem, Rivlin and Thomas [11] devised a number of tests in which the tearing energy can be calculated in terms of applied forces and displacements. Thus, they were able to determine the critical tearing energy for crack growth for a particular vulcanized rubber.

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Many investigators [4, 13, 14] have demonstrated that, the critical tearing energy, T_{cr}, is independent of the geometry and dimensions of the test piece and can be considered as a material property. For component design the tearing energy, T, is calculated for a hypothetical crack and is compared with T_{cr} to determine if the crack will propagate. Thomas [3] has shown that the tearing energy depends on the work required to break a unit volume of material in simple tension in the absence of cracks and the diameter of the notch tip, which measures the bluntness of the notch.

Experimental determination of critical tearing energy becomes complicated due to the unstable tearing or stick-slip tearing which is a well-documented phenomenon in most crosslinked elastomeric materials. The crack does not propagate at a steady rate but arrests and reinitiates at somewhat regular intervals. The force necessary to drive the crack varies widely from a maximum at crack initiation to a minimum at crack arrest. In some cases the crack deviates sideways from a linear path and may circle back upon itself. To suppress unstable crack growth and crack path deviation, Gent and Henry [2] developed a constrained trousers specimen by bonding thin metal shims on opposite sides of the specimen legs. The use of this specimen helped to control the stick-slip and crack-path deviation phenomena. Other works related to the tearing of elastomers are listed in references 1, 2, 8, 9, 10, 12.

In the present work the basic principles of the application of fracture mechanics [15, 16] to rubber are briefly discussed. Results of an experimental study of determining the critical tearing energy of pure tire rubber under mode-I and mode-III loading are presented.

2. TEARING ENERGY

The earliest attempt to formulate a linear elastic theory of crack propagation based on the global energy balance of the cracked body was made by Griffith [5-6]. He used the first law of thermodynamics and postulated that a necessary condition for crack growth is that the energy necessary in creating new fracture surfaces is supplied by the released strain energy in the elastic body. When the surface energy of the material and the crack size are known, the energy criterion can predict the minimum load for fracture. Griffith resolved the paradox arising in the Inglis solution [7] of a sharp crack in an elastic body according to which an infinite stress occurs at the crack tip and, therefore, a body with a crack could sustain no applied load.

The Griffith criterion of crack growth may by expressed as [5, 6]

$$-\frac{dW}{da} > T\frac{dA}{da} \tag{1}$$

where W is the elastic strain energy stored in the body, a is crack length, A is the area of new surface formed by an increase in crack length da, and T is the surface free energy per unit area of the material.

Griffith applied his criterion to predict the strength of glass fibers and to establish the size effect in solids according to which the strength of a material decreases as its size increases up to a limiting value of bulk material for large sizes.

In attempting to find a criterion for growth of a crack in elastomers, application of the critical stress criterion presents considerable difficulties. Indeed, elastomers present large deformation prior to failure, and the solution of the mathematical problem of determining the stress field in the cracked body made of an elastic material is intractable. Furthermore, high stresses are developed to a very small region around the crack tip, so that their measurement cannot be readily carried out.

The Griffith approach can be applied to elastomers since it is not limited to small strains and linear elastic response. However, the reduction of the elastic strain energy in elastomers is not spent only to increase of surface free energy of the cracked body, but is being transformed to other forms of energy, like irreversible deformation of the material. These changes take place in the neighborhood of the crack tip in a relatively small volume of the material compared with the overall dimensions of the body. Thus, it is anticipated that the energy losses in causing an increase of the crack length will be independent of the shape and dimensions of the cracked body and the form of the applied forces. The energy required to grow a crack is characteristic of the material and independent of the test piece geometry. Under such conditions, the Griffith criterion can be applied to elastomers. The region near the tip of the crack will deform very highly with respect to the rest of the body. When the crack of length a in a sheet of thickness t is grown by da an amount of work T_{cr} t dc is done, where T_{cr} is an energy characteristic of the material. When the applied forces do no work during crack growth the crack growth condition is given by

$$-\frac{1}{t}\left(\frac{\partial W}{\partial a}\right)_{\ell} = T_{cr} \tag{2}$$

The suffix l denotes differentiation with constant displacement of the boundaries over which forces are applied. T_{cr} is the critical energy for tearing and is a characteristic property of the material. It is no longer interpreted as the surface free-energy of the Griffith criterion of relation (1). The tearing energy, T, is defined by the left hand side of Eq. (2). Experimental measurements show that when crack propagation is expressed in terms of the tearing energy, the relation is independent of specimen type and geometry. Fatigue crack growth characteristics are also related to tearing energy.

The tearing energy can be determined from the state of affairs in the neighborhood of the notch. For a notch tip of diameter d, T is given by [13]

$$T = d\int_{0}^{\pi/2} W_0 \cos\phi \, d\phi \tag{3}$$

where W_0 is the strain energy density at notch tip surface at a polar angle Ö .

Eq. (3) is similar to the J-integral. It can be simplified as

$$T \cong W_b d \tag{4}$$

where W_b is the average energy density at the tip. W_b is the work required to break a unit volume of material in simple extension in the absence of cracks and is an intrinsic material constant. Eq. (4) indicates that T is directly proportional to d.

3. DETERMINATION OF CRITICAL TEARING ENERGY

Analytical determination of tearing energy in terms of applied forces or displacements for an arbitrarily shaped test piece is formidable due to nonlinear behavior and large deformations of elastomers. In principle, the tearing energy can be determined experimentally by measuring the force-displacement relations for two different crack lengths. The elastic strain energy W is then obtained by integrating the force-displacement curve up to a certain value of displacement. The slope of the elastic strain energy versus crack length curve is the tearing energy according to Eq. (2). When the displacement of the force-displacement curve corresponds to the critical displacement for initiation of crack growth or unstable crack growth the critical tearing energy for initiation or unstable crack growth is obtained, respectively. This process for the experimental determination of tearing energy is usually applied for many different crack lengths. The method is not precise due to the errors introduced by the numerical integrations and differentiations involved. Another drawback is that a set of specimens with different crack lengths should be tested.

Although analytical expressions for the tearing energy in terms of applied forces or displacements cannot be obtained for an arbitrarily shaped specimen, the problem is simplified for certain test piece geometries. In such cases an expression for the tearing energy can be derived without explicit knowledge of the detailed stress distribution of the corresponding elasticity problem. We will discuss two such cases: the trousers specimen and the constrained tension (or shear) specimen.

4. TROUSERS SPECIMEN

The trousers specimen has become a favorite test piece for determination of out-of-plane mode-III critical tearing energy for elastomers. The specimen is a thin rectangular piece cut centrally along its length so that two legs are formed (Fig.1). The legs are pulled in opposite directions out of the plane of the test piece by equal and opposite forces. The expression for tearing energy is

$$T = \frac{2\lambda P}{h} - 2bw \tag{5}$$

where: P = force on legs of specimen
λ = extension ratio in legs (ratio of length of deformed to underformed leg)
h = specimen thickness
b = width of legs
w = strain energy density in the legs

When the specimen legs can be considered inextensible compared to the tearing $(\lambda \cong 1, w \cong 0)$ Eq. (5) is simplified as

$$T = \frac{2P}{h} \tag{6}$$

The rate of crack propagation, $\dot{a}$ when the specimen legs are inextensible (λ=1) is

$$a = \frac{R}{2} \tag{7}$$

where R is the crosshead speed. This means that the rate of tearing is half the crosshead speed of the testing machine.

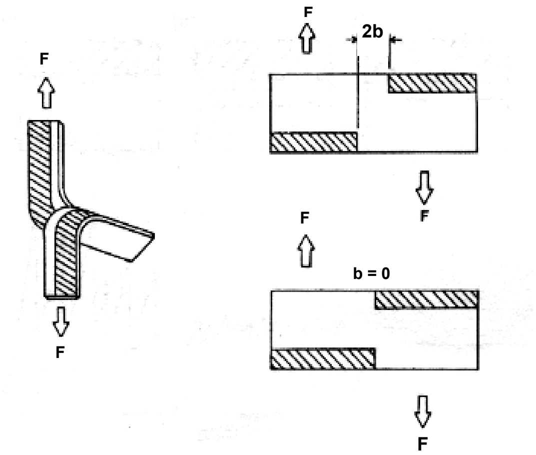
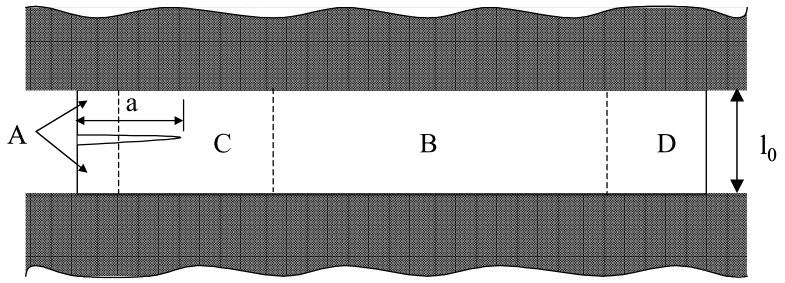


Fig. 1. Trousers Specimen with Shim

The force at which the cut of the specimen first grows is measured. Then Eq. (5) or Eq (6) is used to determine the critical tearing energy.

5. CONSTRAINED TENSION (SHEAR) SPECIMEN

The constrained tension specimen is a wide strip of rubber material attached along its long edges to rigid grips that constrain its lateral deformation (Fig. 2). If a sufficiently long crack is introduced there is an essentially unstrained region A and, provided the width to height ratio is sufficiently high, there is a region B under uniform (homogeneous) biaxial tension. There is also a region C around the crack tip under a complex state of strain and a region D near the uncracked edge subjected to strain due to edge effects.



A: Unstrained region
B: Uniform biaxial tension
C: Complex state of strain
D: Strain due to edges effects

Fig 2. Constrained tension (shear) specimen

If a constant deformation is applied to the specimen, the crack length is increased by da, the complex strain region C is simply displaced along the horizontal direction by a distance da, without undergoing any change in its size, the state of strain and the energy stored in it. The net effect of a crack extension da is a reduction of region B and increase of region A by a volume equal to l_o h(da), where h is the specimen thickness and l_o is the height. The edge region D remains unchanged. Thus, a crack extension da reduces the total elastic energy by dW = (w l_o h) da, where w is the strain energy density (per unit volume) in the constrained (biaxial) tension region. Thus, the tearing energy is

$$T = \frac{dW}{dA} wl_o \tag{8}$$

The value of w is found from the stress-strain relation of a specimen under conditions of constrained tension like those existing in region B.

By comparing the constrained tension and the trousers specimen we observe that in the trousers test the rubber in the legs does not undergo large deformation. Thus, the tearing energy is not substantially affected by the imperfect elasticity of the rubber. In contrast, for the constrained tension specimen the main body of the specimen undergoes substantial deformation. Furthermore, in the trousers test the rate of propagation of the tear is directly related to the rate of separation of the grips of the testing machine (Eq. 6). On the contrary, in the constrained tension test the crack propagation rate should be measured during the test by monitoring the crack length at various time intervals.

6. TYPES OF TEARINTG

The tear process as it is defined by examination of the torn surfaces of different vulcanizates can be classified into two main types: Steady and stick-slip. In the steady tearing the force and rate of crack propagation remain essentially constant, while the torn surfaces are smooth to the naked eye. The tear behavior can be represented by average values of tearing energy and crack propagation rate. In the stick-slip tearing the crack advances in a discontinuous manner, that is, it stops and reinitiates at fairly regular intervals. The tearing force fluctuates from a maximum value at crack initiation to a minimum value at crack arrest. These fluctuations resemble those in certain frictional phenomena, hence the term stick-slip. The torn surface presents some irregularities at the stick (arrest) positions. In certain cases the variation between the maximum and minimum force during crack growth is large, so that an average value of the critical tearing energy is meaningless. Also, the use of an average value of the rate of crack propagation gives only a crude description of the dependence of the energy for tearing on the rate of propagation.

7. MATERIAL

The tire rubber used in this work is a blend of natural rubber (NR) and `polybutadiene (BR). It is vulcanized and filled with carbon black. Table 1 shows the specific composition of the rubber. Since the compound is primarily NR the behavior of the tire rubber is dominated by the behavior of NR. BR is often blended with NR in tire compounds to provide added abrasion resistance. Carbon black fillers are added to increase the compound strength and to protect against ultraviolet degradation. The vulcanizing process adds strength and stiffness. NR is a product most commonly coagulated from the latex of the rubber tree. It exhibits a wide range of beneficial properties including high rebound elasticity, low temperature flexibility and low heat build-up. NR is highly resistant to tearing because of its ability to strain crystallize well above the glass transition temperature. When it is subjected to strain the long molecular chains of the material orient themselves to produce a reinforcing effect. The material becomes anisotropic with higher strength along the strain direction.

Table 1. Composition of Rubber Compound

57% by weight Polymer
30% by weight Carbon Black
Polymer Content:
84% Natural Rubber (NR)
16% Polybutadiene (BR)

8. EXPERIMENTAL

8.1. Mode-III loading

The out-of-plane mode-III critical tearing energy was determined from the trousers test. The trousers specimens had legs 12.6 mm (0.495 in) wide and varying thickness ranged from 0.74 to 1.73 mm (0.029 to 0.068 in.). Initial results revealed a stick-slip tearing mechanism during crack growth. The applied force necessary to propagate the crack varied widely from a minimum at crack arrest to a maximum at crack extension. To reduce the stick-slip tearing constrained trousers specimens were used. The specimens were reinforced locally with two thin steel shims of different widths bonded on opposite

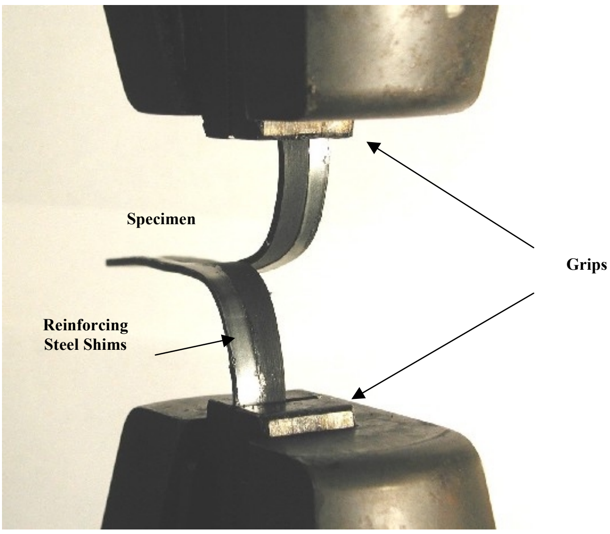


Fig. 3. Trousers Test Setup – Specimen with Steel Shims

sides of the specimen along the crack. The distance b between the metal shims varied between 2.54 mm (0.1 in.) and 20 mm (0.8 in.). To ensure that the crack propagates along its initial plane direction a shallow groove was cut along the crack ligament on both sides of the specimen. Fig. 3 shows a picture of the experimental setup.

Fig. 4 shows a typical load-displacement graph during crack growth for a specimen of net thickness along the crack ligament of 1.45 mm (0.057 in.) after the depth of the two grooves has been accounted for. The distance between the steel shims is 2.54 mm (0.1 in.) and the loading rate is 5.1 mm/min (0.2 in/min). The load reaches a maximum value at crack growth and a minimum value at crack arrest. The mode of crack propagation is characterized by an increase of load with no crack growth followed by a sudden decrease of load as the crack propagates unstably and arrests. This pattern is repeated at fairly regular intervals. The tear surface of a specimen that experienced stick-slip tearing is shown in Fig. 5. Note the "shear cusps" which indicate the sites of tear initiation. At these sites the load drops to a minimum value at crack arrest.

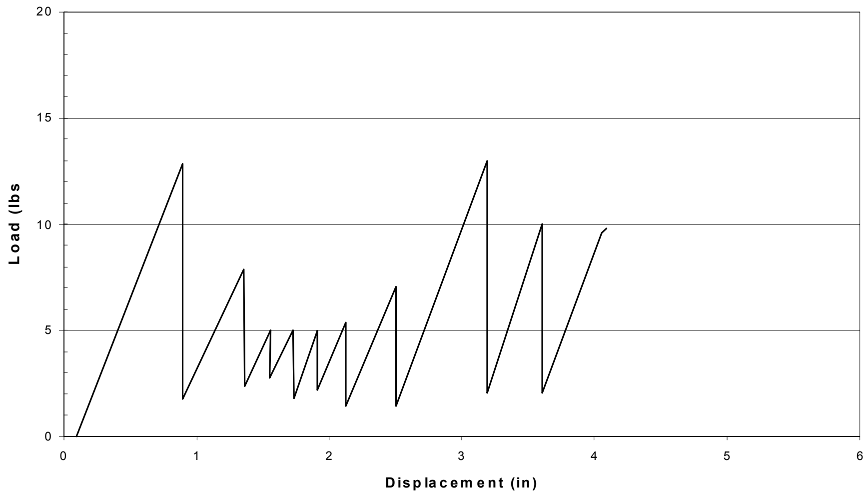


Fig. 4. Trousers test – loading rate 5mm/min

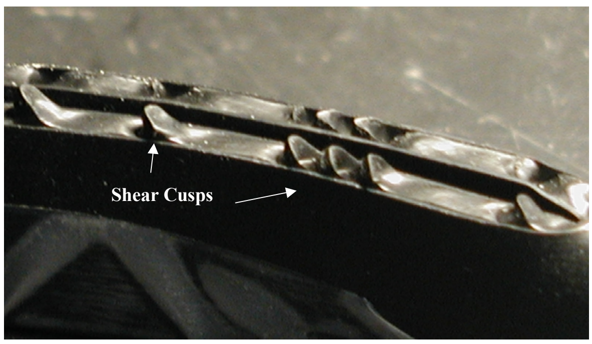


Fig. 5. Image of knotty tear surface

The effect of crack growth rate on the critical tearing energy for applied loading rates between 5.1 and 254 mm/min (0.2 to 10 in/min) was studied. According to Eq. (6) the crack grows at a rate equal to half the rate of the load. Figs. 6 and 7 show the load versus displacement records for crack growth rates of 25.4 mm/min (1.0 in/min) and 76.2 mm/min (3.0 in/min), respectively. The specimen thickness in Figs 7 and 8 along the crack ligament after the two grooves were accounted for was 1.12 mm (0.044 in) and 1.57 mm (0.062 in.) and the distance between the steel shims was b = 5.46 mm (0.215 in.) and 7.62 mm (0.30 in.), respectively.

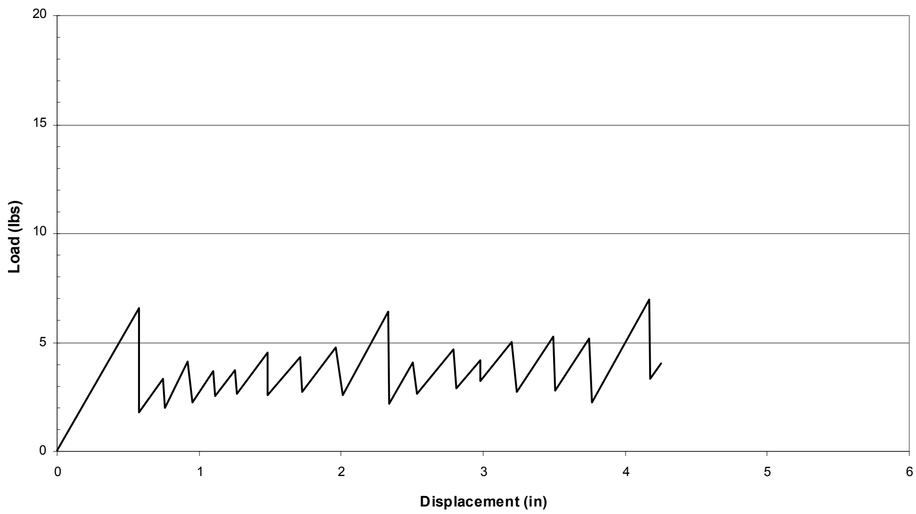


Fig. 6. Trousers test – loading rate 1in/mm

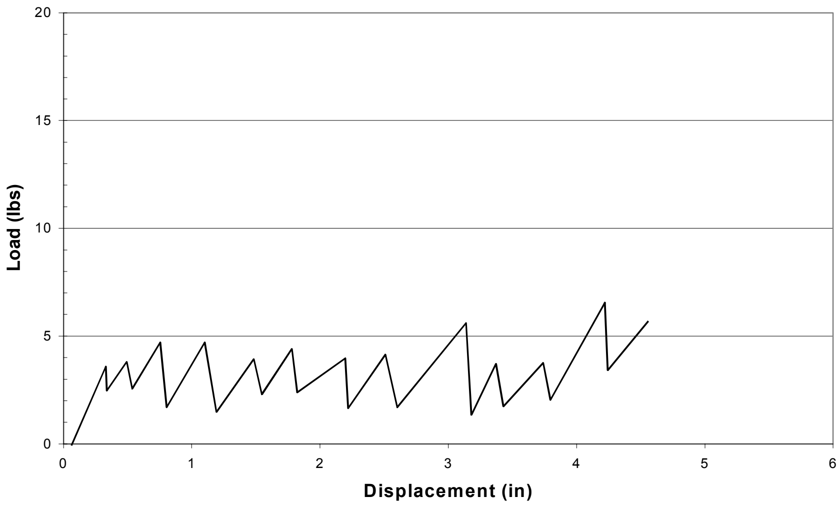


Fig. 7. Trousers test – loading rate 3.0 in/min

8.2. Mode-I loading

A series of constrained tension specimens of dimensions 101.6 x 17.8 x1.9 mm (4 x 0.7 x 0.075 in.) with crack lengths of 38.1, 44.5, 50.4 and 57.1 mm (1.5, 1.75. 2 and 2.25 in.) were loaded in an Instron servohydraulic testing machine. Fig. 8 shows the load-displacement curve up to the point of crack initiation. No stable crack growth as in the case of the trousers test was observed. Crack initiation coincided with rapid catastrophic failure. The load-displacement curve presents a nonlinear sigmoid behavior characteristic of rubber. The stiffness of the curve after a small linear part decreases up to a limiting strain after which it increases. Note that the curves approach each other as the crack length increases up to a limiting crack length of 57.1 mm (2.25 in). Fig. 9 shows a photograph of the tear surface after fracturing the specimen. Note that the fracture surface is smooth without any indication of stable growth.

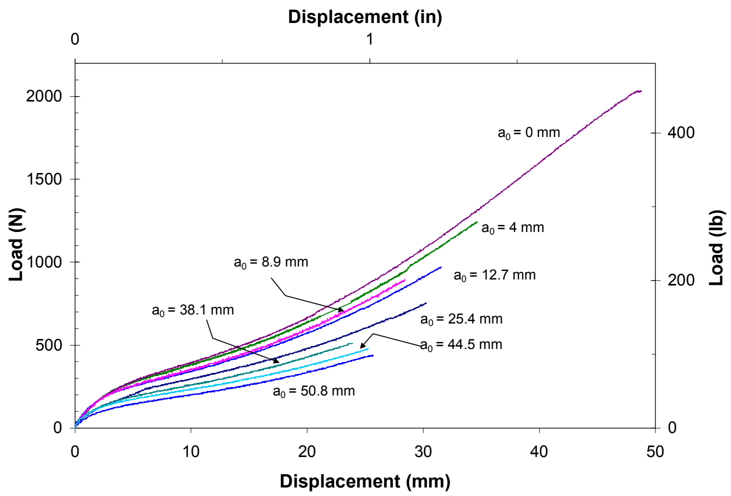


Fig. 8. Load vs. Displacement Curves for Constrained Tension Specimens for Different Crack Lengths

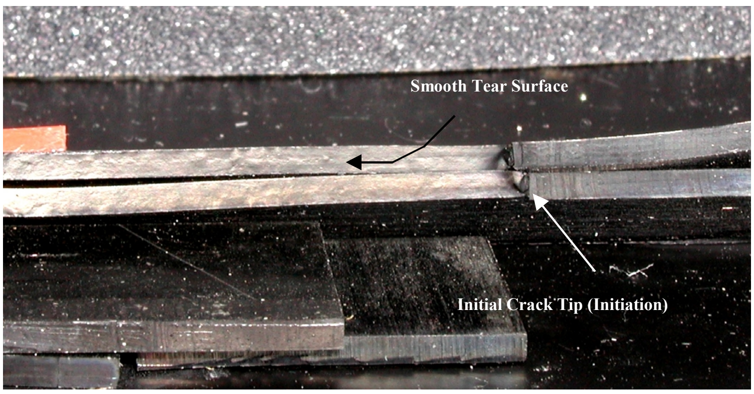


Fig. 9. Image of tear surface from constrained tension test

9. Results and discussion

9.1 Mode-III loading

From the load-displacement records of Figs. 4, 6 and 7 we observe that the force gradually increases with displacement until a maximum is reached. At this point, the force drops with increasing displacement until a minimum is reached. The crack at maximum force initiates, while at minimum force arrest. This cycle of crack initiation and arrest repeats itself at fairly regular intervals. This form of crack growth is known as stick-slip tearing. The crack does not propagate in a self-similar manner at constant speed, but stops and reinitiates at fairly regular intervals. The stick-slip mode of crack growth was reduced, hut it was not eliminated with the bonding of the steel shims to the legs of the trousers specimen.

An explanation of the observed fluctuation of the force from a maximum value at crack initiation to a minimum value at crack arrest can be provided from Eq. (4). As the applied force increases the diameter, d, of the notch at its tip, which measures the bluntness of the notch, also increases up to a value at which the notch starts to propagate. At this point d reaches a maximum value and since the work W_b is a material constant, Eq. (4) suggests that the tearing energy T and therefore the force F (Eq. (6)) for crack growth becomes maximum. As the notch initiates at the maximum load its diameter starts to decrease to a minimum value at arrest, which leads to a minimum value of the applied force.

From the values of the applied force at crack initiation and arrest of Figs. 4, 6 and 7 we can calculate the corresponding critical values of tearing energy. Since the legs of the trousers specimens have been reinforced with steel shims the deformation of the legs is negligible (λ = 1, w = 0). Thus, Eq. (6) can be used for the calculation of the critical tearing energy, T_{cr}. Results of the initiation, arrest and average tearing energy for a crosshead displacement rate of 51 mm/min (2.0 in/min) and a shim separation distance b = 38 mm (0.15 in.) are shown in Table 2.

Table 2. Trousers Test Results

Specimen	**(N/mm)**			**(lb/in)**		
	Initiation	**Arrest**	**Mean**	**Initiation**	**Arrest**	**Mean**
1	44	20	32	250	113	181
2	32	23	27	182	130	156
3	29	25	27	165	141	153
AVERAGE:	**35**	**22**	**29**	**199**	**128**	**163**

From Figs 4, 6 and 7 we observe that the scatter in the force values at crack arrest is smaller than at crack initiation. This result indicates that the tear initiation energy provides a measure of the resistance of the rubber to tearing but cannot be considered as an inherent material property. On the contrary, the arrest critical tearing energy corresponds to a fairly constant crack tip diameter and is an inherent material property. Due to the great difference between the initiation and arrest critical tearing energies, calculation of an average tearing energy is physically inappropriate. A series of specimens with thickness ranging from 0.74 to 1.73 mm (0.029 to 0.086 in.) were tested to study the effect of specimen thickness on the tearing energy. It is found that the tearing energy is independent of specimen thickness.

The effect of crack growth rate on the tearing energy was studied. The rate of applied load varied between 5.1 and 254 mm/min (0.2 and 10 in/min), which means that the crack propagated at a speed half of these values (Eq. (7)). It was found that as the crack propagation rate increases, the fluctuation of the load decreases at both maximum and minimum values, and therefore, the crack grows in a more stable manner at higher crack propagation rates. Furthermore, for all crack propagation rates it was found that the scatter of force values at crack arrest is smaller than at crack initiation. The variation of the arrest and initiation tearing energies versus the rate of loading is shown in Fig. 10. Note that both tearing energies increase as the loading rate increases. However, the arrest energy increases at a much slower rate than the initiation tearing energy. This result in conjunction with the stability of tearing energies at crack arrest suggests that the critical tearing energy at crack arrest can be considered as an inherent material property.

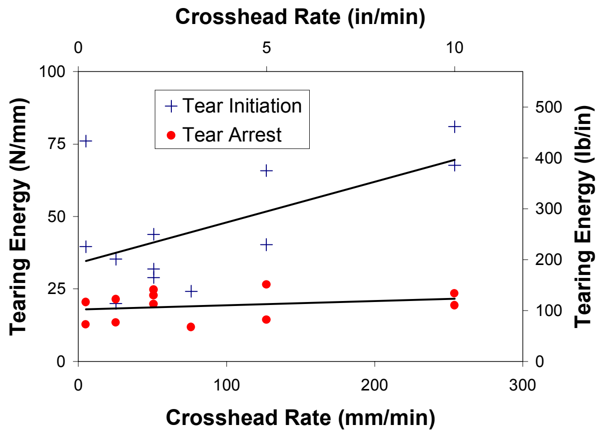


Fig. 10. Effect of loading rate on the initiation and arrest tearing energies

9.2 Mode-I loading

The load-displacement curves of Fig. 8 approach each other and tend to a limiting curve as the crack length increases up to a value of 50.8 mm (2.0 in). For that crack length Eq. (6) can be used for the determination of the critical tearing energy under mode-I loading. A value of 31.3 N/mm (176 Ib/in) was obtained (Table 3). This value is close to the critical tearing energy at initiation for mode-III loading.

10. CONCLUSIONS

The basic principles of the application of fracture mechanics to rubber were briefly discussed. The crack growth behavior and critical tearing energy of tire rubber under mode-I and mode-III loading were determined by using the constrained tension and trousers specimens, respectively. The main results of the study of crack growth behavior of tire rubber are the following:

For mode-III loading:

- The crack grows by a stick-slip mechanism which can be viewed as a process alternating between a blunt crack tip at initiation and a sharp tip at arrest.
- Even for constrained trousers specimens (with steel shims) the development of knotty tearing was not suppressed substantially.
- Crack growth is governed by the values of critical tearing energy at crack initiation and arrest.
- Critical tearing energy at crack initiation is fifty percent higher that at crack arrest.
- The scatter of tearing energy values at crack arrest is much smaller than at crack initiation.
- Critical tearing energy at crack arrest can be considered as an intrinsic material property.
- Arrest and initiation tearing energy increase as the crosshead rate of the application of the load increases.

For Mode-I Loading:

- For the constrained tension specimen the load at crack initiation coincides with the load at unstable crack growth. There is no stable crack growth.
- The critical tearing energy for mode-I is close to the critical tearing energy at initiation for mode-III loading.

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MEHANIKA LOMA GUME

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Osnovni principi primene mehanike loma na gumu ukratko su razmotreni. Značaj problema se javlja usled velike nelinearne deformacije gume, što dovodi do poteškoća u rešavanju problema granične vrednosti naprslog tela od gume. Ponašanje pri kidanju gume može se na podesan način opisati preko kritične energije kidanja koja je karakteristično svojstvo materijala. Prikazani su rezultati eksperimentalne studije na odredjivanju ponašanja u napredovanju prsline i kritičnih energija kidanja čiste gume. Ograničeno istezanje i opitni uzorak sa kracima su svaki ponaosob korišćeni za opterećenje u modu I i modu III. Kod opitnog uzorka sa kracima, sila koja je neophodna za proširenje prsline široko varira od maksimalne vrednosti pri početku stvaranja prsline, do minimalne vrednosti pri zaustuvljanju prsline. To vodi stick-slip (prijanjajuće-klizećem) stabilnom napredovanju prsline, to jest, zaustavljanju prsline, i ponovnim počecima po prilično pravilnim intervalima. U testovima ograničenog istezanja, zapodinjanje prsline pokreće katastrofično napredovanje. Rezultati za kritične energije kidanja za mod I i mod III su dati.