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Failure of Foamed Elastic Materials

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1. INTRODUCTION

The breaking extension of rubber foams is surprisingly low, much lower than that of the corresponding solid rubber. Natural rubber foams, for example, break at extensions of the order of 300% of the unstrained length, whereas the bulk rubber breaks at an extension of about 600%. The tensile strength is low also, being of the order of one-hundredth of that for the bulk rubber when the volume fraction of rubber in the foam is 10%.

Breaking of the rubber threads of which the foam is comprised can often be seen (and heard) at loads approaching the breaking load, particularly in the neighborhood of flaws in the foam. It appears, therefore, that tensile failure is due to the growth of flaws, i.e., it consists of a tearing process which becomes catastrophic at the breaking load.

The tear strength may be calculated for a model structure consisting of a large number of thin threads by means of the characteristic energy criterion developed by Rivlin and Thomas[1] to account for the tear behavior of solid rubber vulcanizates. The tear strength is derived in Section 2 below for a model foam structure, and measured values for a wide range of foam densities are compared with the theoretical predictions.

If the material breaks in simple extension by catastrophic tearing from a small nick in one edge, the energy stored in the specimen at break, i.e., the work required to break, is simply related to the characteristic tearing energy.[2] In Section 3 the work-to-break is calculated from the tear strength of the foam. The measured values are then compared with the predictions of the theory.

2. TEAR OF RUBBER FOAMS

Theoretical Treatment

The amount of work required to advance a tear by unit distance provides a measure of the tear strength of the material. It may be expressed as a characteristic energy $T/2$ per unit area of newly formed surface.[1] For solid rubber the quantity T is found to be independent of the test-piece shape or the type of deformation, and hence describes the tear resistance uniquely.[1,2] It is approximately given by[2]

$$T = Ed$$

where E is the energy required per unit volume to break the material at the tear tip in simple extension and d is the diameter of the tip of the tear, generally of the order of 10^{-2} cm.[2].

For a tear propagated in a rubber foam the characteristic tearing energy T_f will be given similarly by

$$T_f = E_f d_f$$

where E_f is the energy required per unit volume to break the rubber threads at the tip of the tear and d_f is the tear tip diameter. We may expect the latter to be determined by the foam structure—to be, in fact, of the order of the average pore size.

The breaking energy E_f for a network of uniform threads distributed in a cubical array is

$$E_f = {}^1/_3 \nu_r E_r$$

where ν_r is the volume fraction of rubber in the foam and E_r is the energy required to break unit volume of the solid rubber. The factor $^1/_3$ denotes the fraction of threads stretched to break. In practice, distortion of the network will occur and a somewhat larger fraction will be deformed but this is not taken into account in the present simple treatment.

The tearing energy for the foam is, therefore,

$$T_f = {}^1/_3 \nu_r E_r d_f \qquad (1)$$

Experimental Results

The characteristic tearing energy T_f was determined for a number of rubber foams of a wide range of densities and average pore sizes. The preparation of the foams has been described by

Pendle in the Appendix to a previous publication.[3] The test-pieces employed were about 10 cm. long and 4 cm. wide; they were cut from sheets of the vulcanized foams, about 1 cm. in thickness.

A central cut was made from one end of the test-piece to the midpoint, to provide two legs about 2 cm. wide and 5 cm. long. The tip of the cut was formed by a razor blade. The test-piece was essentially similar, therefore, to the "simple extension" test-piece of Rivlin and Thomas,[1] and Greensmith and Thomas,[4] and measurements of tearing force and hence tearing energy were carried out in a similar manner. The end of one leg was secured by a rigid clamp, and the other was attached to one end of a calibrated helical spring so that the force F necessary to cause the cut to propagate by tearing could be determined from the spring extension at which tearing took place. Several determinations were made for each test-piece. The characteristic tearing energies T_f for steady tearing were then calculated by means of the relation[1,4]

$$T_f = 2F/t$$

where t is the test-piece thickness. The average values are listed in Table I.

TABLE I
Measured Tearing Energies and Calculated Tear Tip Diameters

Foam test-piece no.	Volume fraction of rubber, ν_r	Tearing energy, T_f, ergs/cm.^{2}, $\times 10^6$	Calculated tear diameter, d_f, mm.	Observed average pore diameter, d', mm.
1	0.093	0.92	0.74	0.40
2	0.101	1.78	1.32	0.30
3	0.103	1.24	0.90	0.35
4	0.110	1.02	0.70	0.20
5	0.196	2.4	0.92	0.35
6	0.197	3.4	1.30	0.45
7	0.205	2.5	0.92	0.25
8	0.223	3.0	1.02	0.25
9	0.240	2.6	0.82	0.18
10	0.249	3.7	1.12	0.30
11	0.350	4.2	0.90	0.30
12	0.401	2.5	0.47	0.13
13	0.422	3.6	0.64	0.25
14	0.445	6.4	1.08	0.25
15	0.568	7.9	1.04	0.20

The corresponding values of the effective tear tip diameters d_f were calculated by means of eq. (1), and are also given in Table I. The value employed for the breaking energy E_r of the rubber matrix, namely, 4.0×10^8 ergs/cm.^{3}, was obtained from tensile measurements on a cast latex sheet prepared from the same mix formulation and using the same vulcanization conditions as for the foams.

The average pore diameters d', determined by microscopic examination of the foams, are also given in Table I. It is clear that the values calculated for the tear tip diameters d_f are of the same order as, but somewhat larger than, the corresponding diameters d'. The mean value of the ratio of the tear diameter to the pore diameter is about 3.5

For a perfectly regular foam structure the tear tip diameter would be expected to be about twice the pore diameter, due to the random arrangement of pores in space. Imperfections in the foam will lead to local deviations of the tear from a linear front and hence give rise to a correspondingly larger effective diameter at the tip. The observed ratio of 3.5 seems, therefore, not unreasonable.

Some tearing at the tip of the initial razor cut was found to occur for values of the applied force only about one-half of those necessary for steady propagation of the tear. The corresponding values of tearing energy T_f and the effective tip diameter d_f, for the initial tearing from a sharp cut, were therefore only about one-half of those given in Table I.

It appears, therefore, that the characteristic tearing energy for the *initiation* of a tear in a rubber foam may be calculated approximately by means of the simple theoretical treatment outlined above, on the assumption that the tear tip diameter is about twice the average pore diameter. The energy for steady tearing is about twice as large, probably due to deviations from a linear path.

3. TENSILE FAILURE OF RUBBER FOAMS

Theoretical Treatment

Rubber foams appear to fail in simple extension by catastrophic tearing from a flaw—for example, a relatively large pore in one of the test-piece surfaces. The energy T available for tearing at the tip of such a flaw is given by[1]

$$T = 2KlE'$$

where K is a numerical constant having a value of about 2,[1] l is the depth of the flaw, and E' is the energy stored in the bulk of the specimen, per unit volume. Failure occurs when T attains the value of the characteristic tearing energy of the material T_f. The corresponding energy E_f' stored in the bulk material, i.e., the work-to-break for the specimen in simple extension, is therefore given by

$$E_f' = T_f/4l \qquad (2)$$

approximately.

Experimental Results

Measurements were made of the tensile strength and elongation at break of dumb-bell shaped test-pieces, which were cut from sheets of the vulcanized foams, about 1 cm. thick.

The narrow central parallel-sided region of the test-pieces was about 5 cm. long and 1.5 cm. wide, the measurements of elongation being made by means of two reference lines marked on one face 2.5 cm. apart in the unstrained state.

The tensile strength, referred to the unstrained cross-sectional area, and the elongation at break are given in Table II together with the values of the breaking energy E_f' calculated from them on the assumption that a linear relation obtains between the applied load and the corresponding extension. In a check experiment, the values for E_f' obtained in this way were found to be within 10% of those obtained by evaluating the areas under the experimentally determined load-extension relations for four of the foams.

Values of the depth of flaw l from which fracture initiated have been calculated by means of eq. (2) using the measured values for the tearing energy T_f and the breaking energy E_f'. They are also given in Table II, together with the values of the largest pore diameter d_m' observed in a cut surface, about 4 cm.^{2} in area, of each foam. This area was chosen since it is of the order of the area of one face of the test-pieces used in the measurements of tensile strength; it was found, however, that substantially larger pores than the largest observed in the representative areas were extremely rare in the foams employed. Moreover they took the form, where present, of smooth-walled spherical holes, which would not be expected to act as potent flaws.

Reasonably good agreement is seen to obtain between the calculated depth of flaw l and the observed largest pore diameter d_m' in Table II, suggesting that tensile failure occurs by catastrophic tearing from a flaw of the order of the largest pore diameter in length.

TABLE II
Measured Breaking Energies and Calculated Flaw Sizes

Foam test-piece no.	Tensile strength, kg./cm.^{2}	Extension at break, %	Work-to-break, E_f', ergs/cm.^{3}, $\times 10^6$	Calculated depth of flaw, l, mm.	Observed largest diameter, d_m', mm.
1	0.80	250	1.00	2.29	3.5
2	1.74	268	2.33	1.91	2.0
3	1.35	281	1.89	1.63	1.5
4	1.25	270	1.70	1.50	1.5
5	3.10	228	3.55	1.69	2.5
6	3.82	327	6.25	1.36	1.8
7	5.94	365	10.8	0.58	0.8
8	4.60	323	7.45	1.01	1.0
9	4.43	283	6.25	1.04	1.0
10	5.83	370	10.8	0.86	1.0
11	4.90	260	6.35	1.66	1.2
12	7.80	265	10.3	0.61	0.7
13	12.7	350	22.2	0.41	0.7
14	14.4	330	23.7	0.68	1.0

4. DISCUSSION

The experimental results indicate that the tear resistance of rubber foams of a wide range of densities may be calculated to a first approximation from elementary considerations. The theory also predicts a direct proportionality between the tear strength and the average pore size. Although the variation in pore size was not large in the foams examined, this general tendency was clearly shown. Foam 12, for example, possessed relatively small pores and was found to be unusually weak in tearing, while foam 6, which had comparatively large pores, was unusually strong in comparison with other foams of similar densities (Table I).

The work required to break a test-piece in simple extension appears to be determined by a simple tear criterion, that the energy available at the tip of the largest flaw present, which is of the order of the largest pore, is the characteristic tearing energy. In this way the relatively low tensile strength of rubber foams is accounted for.

Equations (1) and (2) suggest that the maximum tensile strength and work-to-break will be obtained for a foam of given density if the pore structure is perfectly uniform and contains no abnormally large pores. A measure of the non-uniformity of the foam structure is provided by the ratio d_m'/d' of the largest pore diameter to the average pore diameter, which ranged from a minimum value of about 3 for foams 7, 10, and 13, to a value of about 9 for foam 1. It is noteworthy that the former three foams all exhibited higher values of tensile strength and work-to-break than other foams of similar densities, while the latter foam was particularly weak (Table II).

The satisfactory agreement found between the theoretically predicted values of tear strength and work-to-break and those observed for foams of a wide range of densities suggests that the basic concepts of the modes of failure are correct.

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Synopsis

A theoretical treatment is given which predicts the tear strength of a foamed elastic material. The energy required to break a test-piece in simple extension is also calculated, on the assumption that tensile failure occurs by catastrophic tearing from a small nick of a similar size to the largest pore present in the test-piece. The behavior is given in terms of the strength of the matrix, the density of the foam, and the pore size. Measurements of the tear strength, tensile strength, and elongation at break are described for natural rubber foams prepared from latex. A wide range of density is covered (0.09–0.5) giving a variation in tear strength of 9:1 and in work-to-break of 24:1. Satisfactory agreement with theory is found in both cases, indicating that the basic concepts of the modes of failure are correct. It is concluded that uniformity of pore size is required for maximum strength, and a large average pore size for high tear resistance.

Résumé

On donne un traitement théorique qui permet de prévoir la tension de rupture d'une matière élastique poreuse. On calcule également l'énergie nécessaire pour rompre un échantillon en extension, en supposant qu'il se produit un manque de resistance par traction exagérée à partir d'une petite entaille, d'une grandeur semblable à celles de plus grandes pores présentes dans l'échantillon. On exprime le comportement en termes de résistance de la matrice, densité de la mousse et la grandeur des pores. On a décrit les mesures de tension de rupture, force de tension et élongation limite pour des caoutchoucs poreux naturels préparés à partir de latex. On couvre un vaste domaine de densités (0,09–0,5) donnant une variation de tension de rupture de 9:1 et de travail de rupture de 24:1. On a trouvé un accord satisfaisant à chaque cas, indiquant que les concepts de base des modes de rupture sont corrects. On a conclu que l'uniformité des grandeurs de pores est requise pour la résistance maximum, et à une grandeur de pore moyenne assez élevée pour une haute résistance de rupture.

Zusammenfassung

Es wird eine theoretische Entwicklung gegeben, die eine Voraussage der Zerreissfestigkeit eines elastischen Schaumstoffes liefert. Ausserdem wird die zum Bruch eines Prüfkörpers bei einfacher Dehnung erforderliche Energie unter der Annahme berechnet, dass die mangelnde Zugfestigkeit durch einen von einer kleinen Einkerbung, deren Gröss der höchsten im Prüfkörper vorhandenen Porengrösse ähnlich ist, ausgehenden katastrophalen Reissvorgang ausgelöst wird. Das Verhalten wird als Funktion der Festigkeit der Matrix, der Dichte des Schaumes und der Porengrösse angegeben. Messungen der Reissestigkeit, der Zugfestigkeit und der Bruchdehnung an aus Latex dargestellten Naturkautschukschaumstoffen werden beschrieben. Ein weiterer Dichtebereich wird untersucht, wobei sich eine Änderung der Reissfestigkeit von 9:1 und eine solche der Brucharbeit von 24:1 ergibt. In beiden Fällen besteht eine befriedigende Übereinstimmung mit der Theorie, was dafür spricht, dass die Grundannahmen für das Zustandekommen des Reissvorganges korrekt sind. Man kommt zu dem Schluss, dass für eine maximale Festigkeit eine einheitliche Porengrösse und für einen hohen Reisswiderstand eine hohe mittlere Porengrösse erforderlich ist.

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