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Rupture of Rubber. XI. Tensile Rupture and Crack Growth in a Noncrystallizing Rubber

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Synopsis

A theory of tensile rupture in a noncrystallizing rubber, a particular instance of a more general theory of rupture in simple extension, is outlined. The theory assumes that failure takes place by growth of a crack from some imperfection in the material where the stress is high locally. The imperfections are considered as being equivalent, in terms of stress concentration effects, to small cracks initially present in the material, and the conditions for crack growth to occur are then treated on the basis of the tearing energy criterion of Part I. It is assumed, by analogy with tearing on a macroscopic scale, that the crack grows continuously with time at a rate, dc/dt, given by: $dc/dt = AT^n$, where A and n are constants and T is the energy expended per unit increase in crack length, per unit thickness of specimen. The predicted relationships of the breaking time to the stored energy density and initial crack length for specimens tested by stretching at uniform rates and by holding at fixed extensions are first compared with the results of model experiments on test pieces containing small tears and cuts. Values of A and n derived from tear test data are used in the theoretical relationships, and it is shown that there is fair agreement with experiment. Results of tests on tensile test pieces containing no deliberately introduced tears or cuts are then shown to be consistent with a failure mechanism of the above type. It appears, however, that the tearing energies in tensile rupture are lower than those observed in tear tests, and reasons for this difference are discussed.

INTRODUCTION

The measured tensile strengths of rubber vulcanizates, in common with those of most other materials, are much lower than would be expected from the magnitude of the molecular forces, and the generally accepted explanation of the discrepancy is that failure originates at imperfections where the stress is high locally.[1] A natural extension of this viewpoint is to treat the imperfections, whatever their origin, as being equivalent in terms of stress concentration effects to small cracks initially present in the material, and then the failure process may be considered as one of tearing from an initial crack. This approach is plausible if the local stresses are high in comparison with the stress in the bulk of the material. In the present paper the predictions of such a failure theory are compared with experiment for the case of tensile rupture in a noncrystallizing rubber.

Two types of tensile test were employed. In the first, test pieces were extended to breaking point at various uniform rates, and, in the second, test pieces were rapidly extended to various fixed extensions and held there until failure occurred. Experiments of this kind afford a means of investigating the nature of the rupture mechanism, provided the rupture properties are not materially affected by the path taken in attaining a given state of deformation.[2] Noncrystallizing gum vulcanizates are probably satisfactory in this respect.

In the following sections a crack growth theory of tensile rupture in noncrystallizing rubbers is outlined, and the theory is compared, first, with the results of model experiments on tensile test pieces containing small initial tears and cuts and, secondly, with the results from tensile rupture tests proper. The rubber used was an SBR gum vulcanizate.

CRACK GROWTH THEORY

A general theory of tensile failure by crack growth has been developed, the theory as applied in particular instances varying only in the crack

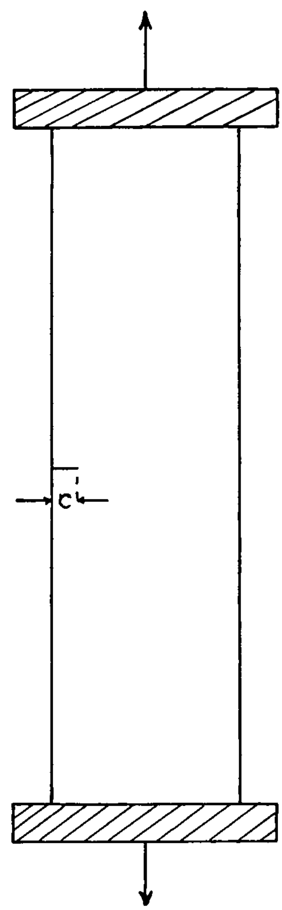

Fig. 1. Test piece with a crack in one edge.

growth law assumed for the rubber or experimental conditions under consideration.[3] In the present case the crack is assumed to grow continuously with time at a rate governed by the imposed extension.

For a test piece strained in simple extension, containing a small crack, cut, or tear in one edge as shown in Figure 1, the condition for tearing to occur is given by:[4]

$$T = 2KcE \tag{1}$$

where K is a numerical factor that varies somewhat with extension,[5] c is the length of the crack measured in the undeformed state, E is the stored energy density in the bulk of the test piece, and T is the tearing energy, i.e., the energy expended per unit increase in crack length, per unit thickness of test piece. The rate of crack growth dc/dt is assumed to increase with T according to the relation:

$$dc/dt = AT^n \tag{2}$$

where A and n are constants, n being positive and greater than unity. It has been found that an equation of this form accurately represents, over several decades of rate of tear propagation, the relationship between tearing energy and rate of propagation as observed in tear tests on noncrystallizing rubbers.[6] Equations (1) and (2) give:

$$dc/dt = A(2KcE)^n \tag{3}$$

which, on integration, gives the crack length c as a function of time t. In carrying out the integrations, the initial length of the crack, c_0 is taken to be small in comparison with the final length (equal to width of the test piece).

Test Piece Held at Constant Extension

In this case E and K are constants, and integration of eq. (3) gives:

$$t_B = 1/A(n - 1)(2K)^n E_B{}^n c_0{}^{n-1} \tag{4}$$

where t_B is the time to break and E_B is the value of E at the breaking extension considered.

Test Piece Extended at a Uniform Rate

The extension of the test piece as a function of time is given by:

$$\lambda - 1 = Vt \tag{5}$$

where λ is the extension ratio and V the rate of extension. An expression for E in terms of λ is next required, and a simple empirical form that is adequate for the present purpose is:

$$E \simeq B(\lambda - 1)^p \tag{6}$$

where B and p are constants. Combining eqs. (5) and (6), the variation of E with time is:

$$E \simeq B(Vt)^p \tag{7}$$

which, on insertion into eq. (3), leads to:

$$t_B = (pn + 1)/A(n - 1)^n(2K)^nE_B{}^nc_0{}^{n-1} \qquad (8)$$

where E_B is the value of E at the breaking point. The variation of K with extension has been neglected in the integration, as it is small in comparison with that of E.[5]

It is apparent from eqs. (4) and (8) that the dependence of the breaking time on the stored energy density at break and on the initial length of the crack is the same for both types of test but the breaking times differ by the factor $(pn + 1)$. It is also apparent that the breaking time is determined almost entirely by the very early stages of tearing, if n is large. For example, with $n = 5$ (a representative value for slow speed tearing in SBR rubber) over 90% of the breaking time will have elapsed before the crack has doubled its initial length. The accuracy of the equations is therefore not greatly affected if appreciable departures from the assumed growth law occur in the later stages of tearing. Modification of eqs. (4) and (8) is necessary, however, if departures from eq. (2) occur in the early stages of tearing, and a particular case of interest in connection with the model experiments will next be considered.

Modified Growth Law

It is assumed that eq. (2) applies for tearing energies less than a critical value T_c, but when $T = T_c$, the rate of propagation can increase indefinitely. A test piece can then be considered to have failed when the crack length attains a value $c = T_c/2KE_B$, as given by the insertion of T_c and E_B into eq. (1). Integration of equation (3) up to this value of c then gives:

$$t_B = [1 - (2Kc_0E_B/T_c)^{n-1}]/A(n - 1)(2K)^nE_B{}^nc_0{}^{n-1} \qquad (9)$$

for a test piece held at a constant extension and:

$$t_B = (pn + 1)[1 - (2Kc_0E_B/T_c)^{n-1}]/A(n - 1)(2K)^nE_B{}^nc_0{}^{n-1} \qquad (10)$$

for a test piece extended at a uniform rate.

EXPERIMENTAL

Tensile Tests

Tensile tests at uniform rates of extension were made with an autographic tensometer that has previously been described.[7] Ring test pieces were used, and these were extended between two small rollers attached, respectively, to the crosshead of the machine and to the cantilever spring used for force measurement. A drum camera recorded the load–crosshead displacement curve. Extensions were calculated as previously described[7] from the crosshead displacement and the undeformed mean circumferential length of the ring. Crosshead speeds and, hence, breaking times or rates of extension were calculated from the driving motor speed as measured with a tachometer. Various rates of extension, from 0.2 to 2000%/sec., were used.

Tensile tests at constant extensions were made with the same machine but with the crosshead coupled to a strong rubber spring instead of the normal motor drive. The crosshead was driven forward at high speed on release of the spring and was brought to rest after a predetermined distance of travel by the impingement of a steel spike on the crosshead against a fixed lead anvil. This arrangement ensured that the crosshead was brought rapidly to rest without undue shock vibration. Load–time records obtained with the drum camera indicated that the stretching of the test pieces was completed in about 30 msec. The length of the test pieces in the extended state was obtained from the measured separation of the rollers, and the times to break were obtained from the load–time curves recorded with the drum camera. The times to break were large in comparison with that for the initial stretching.

In subsidiary model experiments the dependence, at constant extension, of the time to break on the initial length of tear was examined, and for this purpose rectangular test pieces were used, normal grips being substituted for the rollers in the tensometer. A jig was used for clamping the grips at a fixed distance apart on to the undeformed test pieces, and the anvil was maintained at a fixed distance from the stationary grip. Thus the overall extension, as measured between grips, was the same for all test pieces. The actual extension in the central region of simple extension was measured in a subsidiary experiment.

All the tests were carried out at a temperature of 25 ± 1°C.

Tear Tests

Tear data for the material were obtained as described in a previous paper,[6] the tear test piece employed being the "trousers" type, for which the energy supply for tearing is approximately proportional to the applied tearing force and independent of the length of the tear. Two methods of test were used. In the first, the test piece was extended at a uniform rate and the tearing force was measured at intervals over a torn distance of several centimeters once a steady state of tearing had been attained. The tearing energy, T, was calculated from the average force, and the rate of propagation was derived from the rate of extension, this being also an average value. Measurements were made at various rates of extension, three test pieces being used at each rate of extension. In the second method, a constant force was applied to the test piece, and the time taken for the tear to travel a distance of several centimeters was measured once a steady state of tearing had been attained. Again, the measured tearing energies and rates of propagation represent average values. The constant forces were applied by means of weights for rates of propagation below 10^{-3} cm./sec. and by means of a soft rubber spring for rates above this value. The length and stiffness of the spring were so adjusted that the applied force did not decrease by more than 5% for an increase in the length of the tear of 5 cm. The tests were carried out at a temperature of 25 ± 1°C.

Material and Test Pieces

The vulcanizate that was used was prepared from SBR (Polysar S) polymerized at 50°C. and containing 23% of styrene. The vulcanizing recipe, in parts by weight, was: rubber, 100; sulfur, 1.75; zinc oxide, 5; stearic acid, 2; Santocure, 1; and antioxidant, 1. The mix was cured for 50 min. at 145°C. Separate batches of sheets were used for the model experiments and the tensile tests proper, each batch being prepared from a single mixing. The batches differed slightly in physical properties, that for the model experiments being lower in stiffness and tensile strength but higher in breaking extension than the other. Tear data were obtained on both batches of material.

Ring test pieces were cut with a double-bladed, rotary cutter from sheets about 3 mm. thick. The internal diameter of the rings was approximately 2 cm., and their thickness (equal to the difference between the internal and external radii) was approximately 0.7 mm. For the model experiments, small tears of controlled length were made in the rings in the following manner.

A small razor cut about $^1/_4$ mm. in length was first made in the minor (thickness) surface of the ring, a jig being used for this purpose so as to produce a cut of controlled length. The ring was then extended sufficiently to produce tearing from the cut. The growth of the tear across the width of the ring was examined under a microscope and the extension suitably adjusted to keep the rate of growth below 10^{-2} cm./sec. The ring was relaxed when the tear had grown about $^1/_4$ mm. from the initial razor cut, the total length of the tear then being about $^1/_2$ mm. The lengths of these tears were measured in the relaxed state with the microscope and eyepiece scale; the maximum variation in the lengths was 12%.

Rectangular tensile test pieces for the model experiments were 12 cm. long and 3 cm. wide, and were cut with a template from sheet about 1 mm. thick. Tears of various lengths were produced in these test pieces in a manner similar to that described above. An initial razor cut was first made by hand in one edge of each test piece, the length of the cut varying from about $^1/_4$ mm. to about 3 mm. A tear was then developed as previously described, being allowed to grow a distance of about $^1/_4$ mm. before the test piece was relaxed.

Test pieces for the tear tests were 10 cm. long and 4 cm. wide and were cut from sheet about 1 mm. thick. A cut about 5 cm. long was made in each test piece to form two equal width "legs" by which the test piece was gripped.

RESULTS

Model Experiments

The tear data obtained with the trousers test pieces are given in Figure 2. They conform to the pattern previously noted for this type of vulcanizate.[6,8]

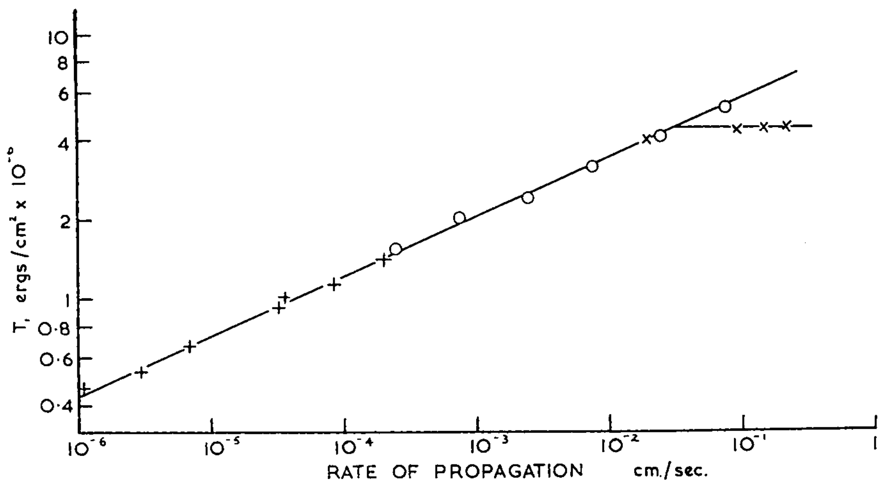

Fig. 2. Tearing energy T vs. rate of tear propagation (data from tear tests): (O) uniform rates of extension, constant forces; (+), dead loads; (×) soft spring.

Thus, at rates of propagation below 3×10^{-2} cm./sec. the results are independent of the method of test and conform to eq. (2), the values of the constants A and n of this equation being as shown in Table I. At rates of propagation above this value, however, the results vary with the method of test. The constant force method gives a fair approximation to the critical tearing energy type of behavior considered in deriving eqs. (9) and (10), and the critical energy, T_c, derived from the data is given in Table I. No critical condition is apparent with the constant rate method.

TABLE I
Tear Parameters from the Data of Figure 2

A, c.g.s. units	n	T_c, ergs/cm.^{2}
8×10^{-32}	4.45	4.4×10^6

The first of the above regions is the most important for the model tensile tests, as the strains in the test pieces and the lengths of the initial tears were such that the tearing energies in the crucial early stages would lie mostly below the critical value. However, it is pertinent to consider which type of tear behavior is appropriate in the cases where this value was exceeded. Of the two test methods employed in the model experiments that of constant extensions corresponds most closely to the constant force method of the tear tests, and the rupture behavior could therefore be expected to be conditioned by a critical tearing energy. The second tensile test method, however, corresponds more closely with the constant rate of extension method of the tear tests, and so a critical tearing energy may not be appropriate in this case.

The model experiments on tensile test pieces containing initial tears of various lengths are next considered. The test pieces were held at an extension of 85%. The stored energy density at this extension, required for comparison of theory and experiment, was obtained from load–extension

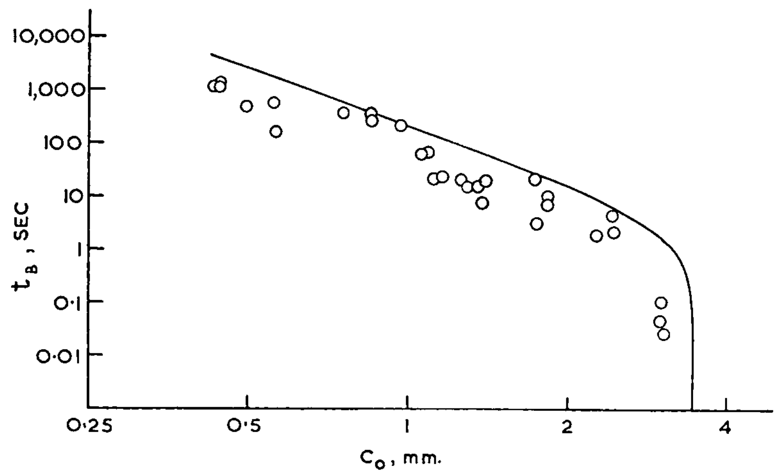

Fig. 3. Dependence of breaking time t_B on initial length of tear c_o at constant extension: (O) experimental results for individual test pieces; (——) theory, eq. (9).

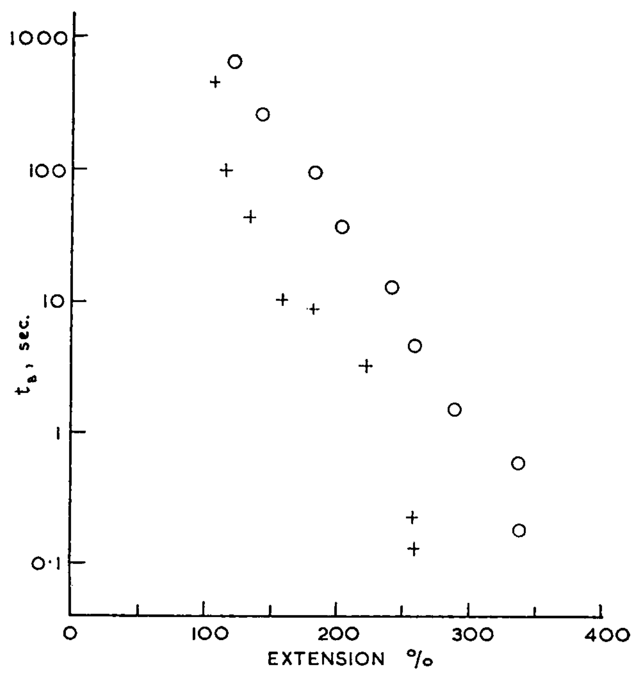

Fig. 4. Dependence of breaking time t_B on breaking extension for test pieces with initial tears of constant length: (O) uniform rates of extension; (+) constant extensions. Plotted points represent mean values for about four test pieces.

measurements on a dumbbell specimen of the same rubber. Results showing the dependence of the time to break t_B on the initial length of tear, c_0, are given in Figure 3. The plotted points are the experimental measurements for the individual specimens, and the curve is that calculated from eq. (9) with a value for the stored energy density at break E_B as obtained above and a value for K appropriate to the extension employed,[5] together with values for A, n, T_c obtained from the tear test data (Table 1). The predicted dependence of t_B on c_0 is in substantial agreement with experiment. The theoretical values of t_B are, however, slightly higher than the experimental values, and this was found to be the case also in subsequent experiments.

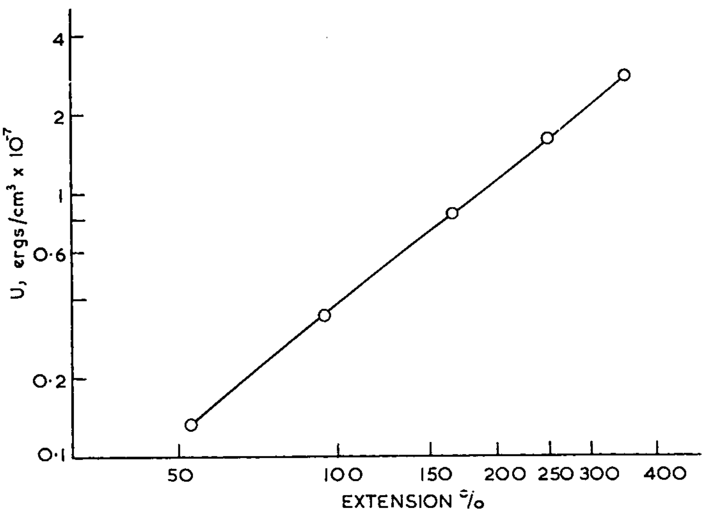

Fig. 5. Double logarithmic plot of work of extension/unit volume U vs. extension. Rate of extension = 0.19%/sec.

Figure 4 gives the experimental results obtained by both types of tensile test with the ring test pieces containing initial tears of constant length. The time to break is shown plotted against the breaking extension, each point representing the mean of about four measurements on individual test pieces. The constant extension method of test gives the shorter breaking times, as predicted by theory, but for a quantitative comparison the stored energy density is required, and this was obtained in the following way.

The work of extension per unit volume, U, for an untorn ring extended at the lowest rate employed experimentally (0.19%/sec.) was computed for various extensions from the area under the measured load-extension curve; U is shown plotted against extension in Figure 5. It was assumed that U represents the stored energy density, E, under the various conditions of the model experiments, and values of E_B appropriate to the breaking extensions were accordingly obtained from this curve.

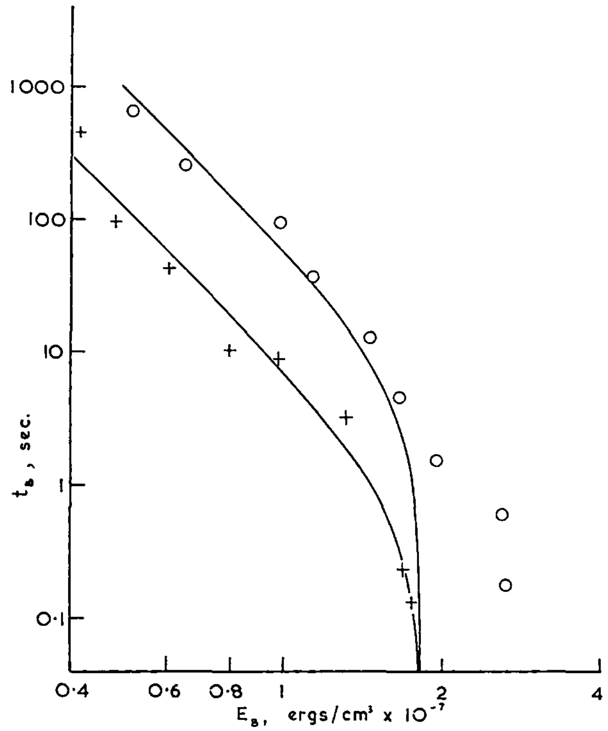

Fig. 6. Dependence of breaking time t_B on stored energy density at break E_B for constant initial length of tear (data of Fig. 4 replotted): (O) results for uniform rates of extension; (+) results for constant extensions; (——) theory, eqs. (9) and (10).

The experimental results of Figure 4 have been replotted in Figure 6 as time to break, t_B, against stored energy density to break, E_B. The curves shown in the figure were calculated from eqs. (9) and (10) with values for A, n, and T_c as given in Table I and with appropriate values for K (varying from 2.0 at 100% extension to 1.65 at 250% extension[5]). The value of p used in eq. (10) was 1.6, the slope of the best straight line through the experimental data for U shown in Figure 5 [cf. eq. (6)]. The value of c_0 that was used was that giving the best fit of eq. (9) with the experimental data for the constant extension method of test, this procedure being adopted to remove any discrepancy between the absolute values of the theoretical and experimental breaking times (cf. Fig. 3). The theoretical curves show fair agreement with experiment in the dependence of the breaking time on the stored energy density at break and in the relationship between the breaking times, except at short breaking times. The disparity at short breaking times is confined to the uniform rate of extension method of test and is of the kind that would be expected if, as previously suggested, a critical tearing energy is inappropriate in this case.

The value of c_0 the initial length of the tear that was used above in eqs. (9) and (10) was 0.72 mm., and the mean of the measured initial lengths was

0.46 mm. This difference corresponds to about a factor of 3 in breaking times, about the same as in Figure 3. It appears, therefore, that breaking times calculated for the tensile test pieces from the trouser tear test data are about a factor of 3 larger than the experimental values. This, although somewhat greater than experimental error, is not large in comparison with the fluctuations in rate of tear propagation commonly observed in trouser tear tests, and is believed to be due to slight differences in the roughness of the tips of the tears in the two cases.

Some additional results which illustrate the influence of tip roughness were obtained with rings containing small razor cuts. The dependence of the breaking time on the stored energy density at break was similar to that found previously, but the value of c_0, the initial length of cut, required to fit theory and experiment was about a factor of 3 larger than the measured lengths of the razor cuts. A razor cut therefore produces a higher stress concentration, i.e., has a sharper tip, than a tear of the type under present consideration.

Tensile Rupture Tests

The results of the tensile rupture tests proper, i.e., the tests on rings containing no deliberately introduced cuts or tears, are shown in Figure 7 in which the breaking times are plotted against the breaking extensions for the two types of test. The plotted points represent mean values for about four

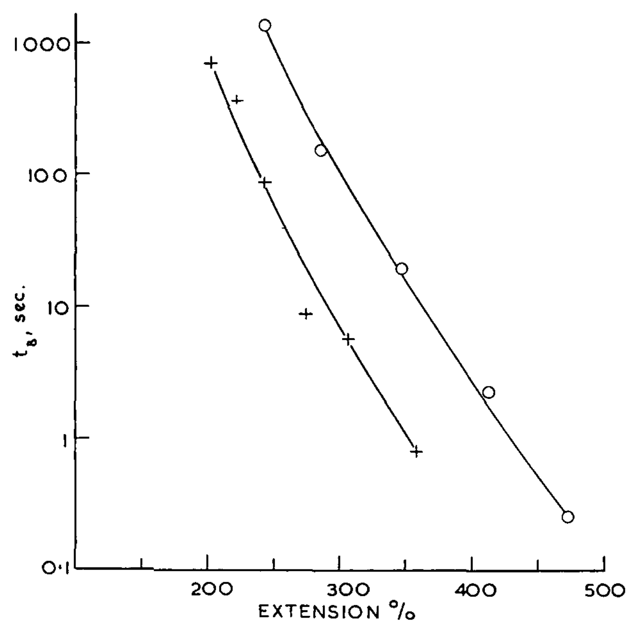

Fig. 7. Dependence of breaking time t_B on breaking extension for tensile rupture proper: (O) uniform rates of extension; (+) constant extensions. Plotted points represent mean values for about four test pieces.

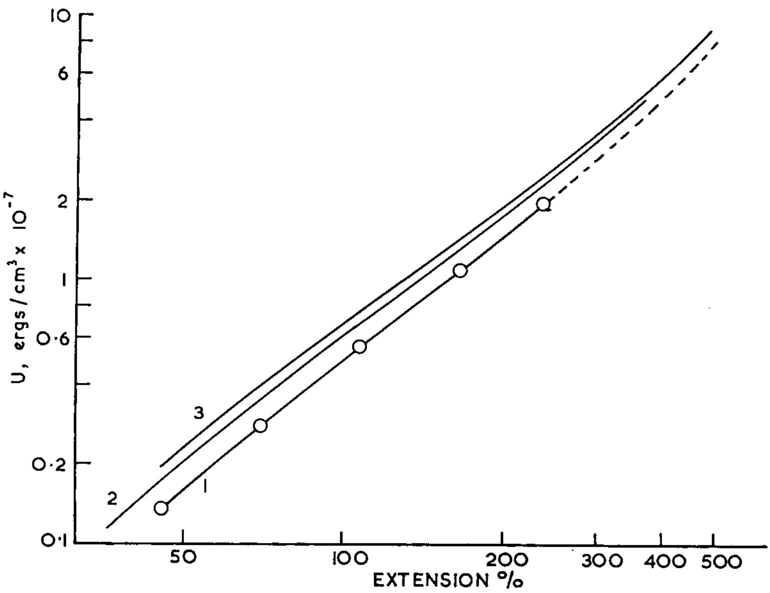

Fig. 8. Double logarithmic plot of work of extension/unit volume (U) vs. extension a various rates of extension: (*1*) 0.19%/sec.; (*2*) 190%/sec.; (*3*) 1900%/sec.

test pieces. As in the model experiments, the breaking times observed in the tests at constant extensions are shorter than those for the tests at uniform rates of extension.

The stored energy density at break, E_B, was estimated in the same manner as for the model experiments. Figure 8 shows the experimental curve (curve *1*) of work of extension per unit volume, U, against extension from which the values of E_B appropriate to the breaking extensions were obtained. The data through which the curve is drawn were obtained from load–extension measurements on a ring extended at the lowest experimental rate (0.19%/sec.). The curve was extrapolated to high extensions by using as a guide the curves of U against extension for specimens extended at higher rates; these additional curves are shown in the figure.

Figure 9 shows the data of Figure 7 replotted as time to break against stored energy density at break. It is apparent that it is not necessary to invoke a critical tearing energy to describe the rupture behavior, and accordingly eqs. (4) and (8) were used in calculating theoretical curves for comparison with these results. The parameter K was assumed to be a constant for these calculations, as it has only been evaluated[5] up to extensions comparable with the lowest of the breaking extensions in the present experiments. The numerical constant p was taken to be 1.7, the value giving the best fit of eq. (6) with the relevant portion of curve *1* of Figure 8, and values for n and $2K(n-1)(2Kc_0)^{n-1}$ were chosen so as to give the best fit of eq. (8) with the experimental data for uniform rates of extension, these same values then being used in eq. (4). There is satisfactory agreement

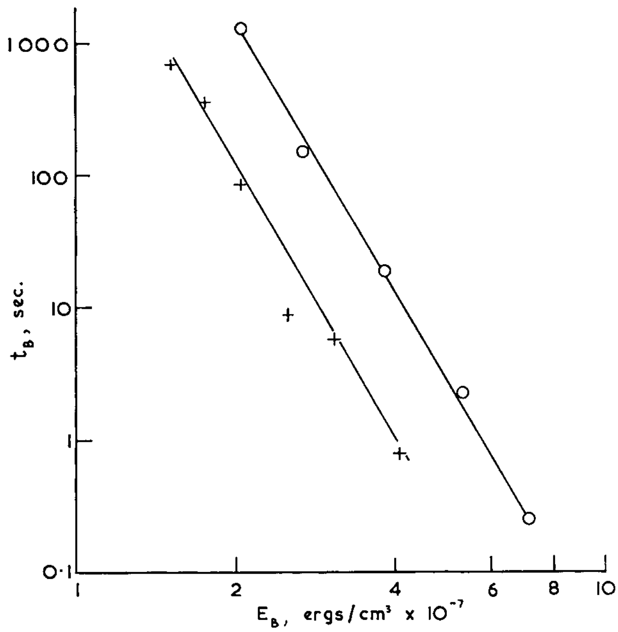

Fig. 9. Dependence of breaking time t_B on stored energy density at break E_B (data of Fig. 7 replotted): (O) results for uniform rates of extension; (+) results for constant extensions; (——) theory, eqs. (4) and (8).

between theory and experiment in the dependence of the breaking time on the stored energy density at break and in the relationship between the breaking times for the two types of test. The value of n that was used was 6.8.

The above value for n is appreciably higher than that derived from trouser tear test data (cf. Table I). The value obtained does, of course, depend on the assumptions made concerning the variation of K with extension. An increase in K of about 75% from 200 to 350% extension would be required to reduce n to a value comparable with that from trouser tear test data, and this would somewhat impair the agreement between theory and experiment. A slight decrease in K over this range of extensions seems the more likely possibility as judged from existing data,[5] and a decrease of up to 25% would, if anything, improve the agreement between theory and experiment. A decrease in K with extension would imply a value for $n > 6.8$.

DISCUSSION

The crack growth theory of tensile failure is substantially confirmed by the model experiments for the case of macroscopic initial cracks. The theory correctly predicts the relationship between the breaking times for different methods of test. Also, the dependence of breaking time on stored energy density and initial crack length is substantially as predicted from the tear test data.

In the case of tensile rupture proper, i.e., no deliberately introduced cuts or cracks, there is agreement between theory and experiment as to the relationship between the breaking times for different methods of test. The results are therefore consistent with a mechanism of failure by crack growth from microscopic cracks or other stress raisers initially present in the material. This finding is of course not dependent on the tearing energy-rate relation for tensile rupture being the same as for the tear tests, and it remains to consider whether or not the tearing is actually identical in the two cases, i.e., whether or not the tearing energy is the same for equal rates of propagation.

It has been noted that the exponent n of the tearing energy-rate relation [eq. (2)] required to fit theory and experiment was apparently appreciably higher than the value obtained from the tear data (see Table I). The high n value does not appear to be consistent with identical tearing in the two cases, even allowing for the possibility that the initial rates of propagation in tensile rupture may lie outside the range of rates for which the particular n value of Table I is appropriate. The tearing energies in tensile rupture must accordingly be lower than those in the tear tests, for equal rates of propagation.

If, on the other hand, the high n value is rejected and it is assumed that the values of A and n [eq. (2)] are the same as those for the tear tests, then a value for c_0, the initial length of the crack, may be calculated. It should be noted that this value simply expresses the stress concentration effect of the initial flaw in terms of an equivalent length of a tear of the type observed in the tear tests and does not necessarily imply the existence of a crack of such dimensions. The value of c_0 obtained is about 10^{-2} cm. and this, as an expression of stress concentration, seems too high to be physically realistic. The conclusion is, again, that the tearing energies in tensile rupture must be lower than those for the tear tests, and this is a not unexpected result for the following reasons.

It has previously been observed that there are scale effects in tearing, tear resistance being found to decrease as the thickness of the test piece is reduced.[9,10] In the crucial early stages of tearing in the tensile tests, when the tear is spreading out from the rupture origin (usually at or near the junction of the major and minor faces of the specimen), both the distance travelled by the tear and the effective thickness of material traversed will be several orders of magnitude smaller than in the tear tests. The difference in the scale of tearing in the two cases is thus very great, and differences in tearing energy could accordingly be expected. These differences are probably associated with the roughness of the tip of the tear. Previous observations have shown the pronounced influence of tip roughness on tearing energy, increased roughness being associated with higher energy.[11] The roughness referred to is on a macroscopic scale, and in tear tests of the type considered it is of the order of tenths of a millimeter. Clearly, roughness of this magnitude could not be developed in the small scale tearing of the tensile tests.

In a previous paper[11] it was shown that the tearing energy values obtained for an SBR gum vulcanizate in trouser tear tests could be plausibly accounted for semiquantitatively in terms of strength of the material as measured in tensile tests. This is the reverse of the procedure adopted in the present paper, but there is not necessarily any inconsistency as the tear and tensile rupture parameters involved do not appear to be identical in the two cases because of scale effects. Thus, in considering tensile rupture in terms of tearing, as at present, it has been noted that the tearing energies involved in tensile rupture appear to be lower than those observed in trouser tear tests, and, correspondingly, in considering tearing in terms of tensile rupture it has previously been pointed out[11] (see also Reznikovskiĭ and Lukomskaya[12]) that the strength of the material at the tip of a tear will be higher than the strength as measured in normal tensile tests because of the disparity in the effective specimen size. Scale effects of this sort would be expected in a material containing flaws or other stress raisers.

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Résumé

Une théorie de la rupture de tension chez un caoutchouc non-cristalisable, exemple particulier d'une théorie plus générale de rupture en simple extension, est exquissée. La théorie dit que les défauts se produisent par croissance d'une fissure provenant d'imperfections dans le matériel ou la tension est hautement localisée. Les imperfections sont considérées comme étant équivalentes en termes d'effets de concentration de force, à de petites fissures initiallement présentes dans le matériel et les conditions pour que la croissance de la fissure se présente sont alors traitées sur la base du critère d'énergie d'arrachement de la Partie I. On peut assurer, par analogie avec l'arrachement sur une échelle macroscopique, que les fissures croissent continuellement avec le temps d'une vitesse dc/dt donnée par $dc/dt = AT^n$, où A et n sont des constantes et T est l'énergie dépensée par unité d'accroissement de la fissure et par unité d'épaisseur du spécimen. Les relations prédites entre le temps de rupture et la densité d'énergie formée et la longueur initiale de la fissure pour les spécimens étudiés (*a*) par allongement à des vitesses uniformes et (*b*) en conservant des extensions fixes, sont d'abord comparées avec les résultats d'expériences modèles sur des pièces test contenant de petites déchirures ou coupures. Les valeurs de A et n dérivées des données des déchirures test sont employées dans la relation théorique et ceci montre qu'il y a un accord parfait avec l'expérience. Les résultats des tests sur des pièces-test ne contenant pas délibérement des déchirures introduites ou des coupures, montrent alors un accord parfait avec un mécanisme de rupture du type ci-dessous. Il apparaît cependant que les énergies d'arrachement dans la rupture de tension sont plus basses que celles observées dans les déchirures-test et on discute les raisons de cette différence.

Zusammenfassung

Als Spezialfall einer allgemeineren Theorie des Reissens bei einfacher Dehnung wurde eine Theorie des Reissens durch Zug in nichtkristallisierendem Kautschuk entwickelt. Es wird angenommen, dass der Bruch durch das Wachstum eines Risses von gewissen Fehlstellen des Materials mit hoher lokaler Spannungskonzentration ausgeht. Die Fehlstellen werden hinsichtlich der Spannungskonzentrationseffekte als kleinen, anfänglich im Material vorhandenen Rissen äquivalent betrachtet und die Bedingungen für das Risswachstum auf der Grundlage des Rissenergiekriteriums aus Teil I behandelt. In Analogie zu makroskopischen Zerreissvorgängen wird angenommen, dass der Riss kontinuierlich mit der Zeit mit einer Geschwindigkeit dc/dt wächst, dei durch $dx/dt = AT^n$ gegeben ist, wobei A und n Konstanten sind und T die für eine Zunahme der Risslänge um eine Einheit, bezogen auf die Dickeneinheit der Probe, aufgewendete Energie ist. Für Proben, die bei der Prüfung (a) mit gleichmässiger Geschwindigkeit gedehnt und (b) auf einer gegebenen Ausdehnung gehalten werden, wurden Beziehungen zwischen Bruchzeit und gespeicherter Energiedichte sowie anfänglicher Risslänge vorausgesagt und zunächst mit den Ergebnissen von Modellversuchen verglichen, die an Proben mit kleinen Rissen und Einschnitten durchgeführt wurden. Bei Verwendung der aus Zerreissversuchen ermittelten Werte von A und n in den theoretischen Beziehungen ist die Übereinstimmung mit dem Experiment gut. Die Ergebnisse der Untersuchung an Proben ohne absichtlich eingeführte Risse oder Einschnitte stehen mit einem Bruch-Mechanismus des obigen Typs im Einklang. Anscheinend ist jedoch die Rissenergie beim Zugbruch niedriger als der bei Zerreissversuchen beobachtete Wert. Ursachen für diesen Unterschied werden diskutiert.

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