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Rupture of Rubber. VIII. Comparisons of Tear and Tensile Rupture Measurements

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INTRODUCTION

In previous papers of this series[1-3] a criterion for tearing of thin sheets of rubber vulcanizates was established on the basis of a characteristic tearing energy, the criterion being applicable either to the initiation of tearing at an incision or to the continuous propagation of a tear. An interpretation of the tearing energy in terms of the strength of a rubber as measured in tensile rupture tests was given,[2] and in the present paper this is used in an attempt to relate tear and tensile rupture measurements, taking into account the observed effects of the speed of the test on such measurements.[4-6] Data obtained from the tensile rupture measurements given in the preceding paper[6] (Part VII) are first compared with the energy to initiate tearing at an incision with a tip of semicircular form. The data are then compared with the tearing energy for tears propagated at various rates.

RELATIONS BETWEEN TEAR AND TENSILE RUPTURE MEASUREMENTS

According to the criterion,[1] the condition for tearing to occur when the applied forces do no work is

$$-(1/h)(\partial W/\partial c)_l = T$$

where h is the thickness of the test piece in the undeformed state, c is the length of the incision or tear in the undeformed state, W is the total strain energy in the test piece, and T is a characteristic tearing energy. The subscript l denotes differentiation carried out under constant displacement of boundaries over which forces are applied. Thus, $-(1/h)(\partial W/\partial c)_l$ represents the supply of energy for tearing and T the energy expended, T being interpreted as a dissipation of energy.[1] Thomas[2] has derived the relation between the strain distribution around the tip of an incision and $-(1/h)$ $(\partial W/\partial c)_l$. From this relation he obtained for the energy to initiate tearing at an incision with a semicircular tip:

$$T \simeq Ed \tag{1}$$

where E is the work done/unit volume in deforming the rubber at the tip to breaking point and d is the diameter of the tip in the undeformed state; d is assumed to be sufficiently large in comparison with the thickness of the test piece for the tip to be substantially in simple extension. Thomas confirmed experimentally that T was proportional to d and that T/d was comparable with the work to break/unit volume E measured in a tensile rupture test.

The approximate validity of eq. (1) for the initiation of tearing at an incision gives grounds for considering the equation to be applicable also in continuous tearing, d now being regarded as an effective diameter of the tip of the tear and a property of the material. Thomas[2] considered that an effective diameter could be ascribed to the tip of a tear on the grounds that irregularities develop at the tip and extend the zone over which high strains must be developed to produce rupture. In accord with this supposition, the value of d required to fit tear and tensile rupture measurements was found to be comparable in magnitude with the irregularities observed in the torn surface.[2] In applying eq. (1) to continuous tearing it is supposed that, as the tear increases in length by an amount Δc, a volume of rubber $h\Delta cd$ is deformed to breaking point and an amount of work $Eh\Delta cd$ is done. It is further supposed that none of the work done is recovered, strain energy stored in the volume $h\Delta cd$ being dissipated when rupture occurs, so that $Eh\Delta cd$ may be equated with the energy $Th\Delta c$ expended in the growth of the tear. In the type of tear test piece considered in the present context, the tear is propagated into undeformed material, and E is therefore the work done/unit volume in taking the rubber from the undeformed state to the breaking point.

The rate of extension of the rubber at the tip of a tear will vary with the rate of propagation of the tear. An approximate relation between the rate of propagation and the rate of extension at the tip may be derived as follows. It is assumed that, for a tear propagating at a speed R, the strain in the neighborhood of the tip falls to zero at a certain distance l_0 ahead of the tip and that l_0 is proportional to the effective diameter of the tip, d. Assuming also that the rubber in the region of the tip is approximately in simple extension and denoting the extension ratio at the tip by λ_t, the rate of extension V of the rubber approaching the tip is given by:

$$V \simeq (\lambda t - 1)R/l_0$$

which, on rearrangement, yields:

$$R \simeq [(l_0/d)/(\lambda_t - 1)]Vd \qquad (2)$$

The value of $l_0/d(\lambda_t - 1)$ in eq. (2) was obtained as described below from measurements of the static strain distribution near the tip of an incision in a test piece of the type used for tear measurements. Evaluation of $l_0/d(\lambda_t - 1)$ in this way restricts the application of eq. (2) to low rates of propagation.

A test piece of the shape shown in Figure 1 was cut from a sheet of natural rubber gum vulcanizate of about $1^1/_2$ mm. thickness. The tip of the incision was semicircular and 1.5 cm. in diameter. Lines about 2 mm. in length were marked on the test piece, as shown, and the lengths of the lines and their respective distances from the tip of the incision were measured with a travelling microscope. The test piece was then extended as shown and the lengths of the lines were again measured to give the extension ratio λ at various distances from the tip of the incision. λ is plotted against l/d in Figure 2, l and d being, respectively, the distance from the tip and the diameter of the tip referred to the undeformed state. The extension ratio does not decrease linearly with distance from the tip as assumed in deriving eq. (2). However, if l_0 is defined as the distance at which λ falls to some low value (say, 1.1 or 1.01), $l_0/d(\lambda_t - 1)$ is found to be nearly independent of the extension ratio λ_t at the tip. Equation (2) may then be written:

$$R \simeq AVd \qquad (3)$$

where A is treated as a constant and V now represents an average rate of extension for the rubber approaching the tip of the tear. In applying eq. (3), A has been assigned a value of 0.75, this being the value of $l_0/d(\lambda_t - 1)$ when l_0 is taken as the distance at which λ falls to 1.01.

Equations (1) and (3) are used, in the experimental comparisons of tear and tensile rupture measurements, to relate the tearing energy for tears propagated at various rates and the work to break/unit volume measured in tensile rupture tests on specimens extended at various rates. In the tensile rupture tests the specimens were extended at uniform rates, and, in using eq. (3), it is assumed that the effect on the strength properties of the material of a nonuniform rate of extension of average value V is to a first approximation the same as extension at a uniform rate V.

In the case of tearing at an incision a relation equivalent to eq. (3) between the rate of extension of the rubber at the tip of the incision and the overall rate of extension (or rate of loading) of the test piece is not readily derived. However, the time taken in extending the test piece to breaking point provides a measure of the average rate of extension of the rubber at the tip of the incision, and

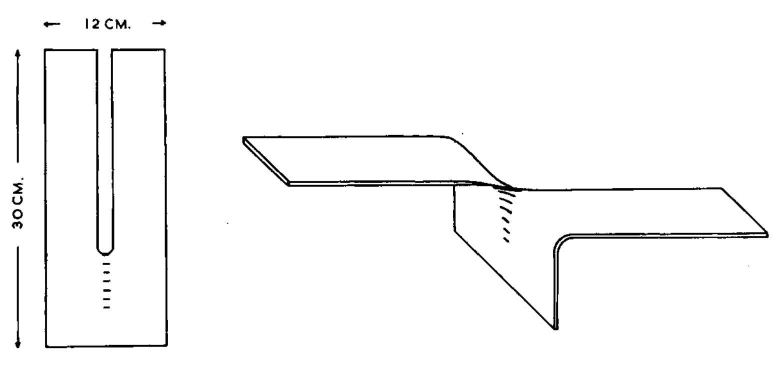

Fig. 1. Test piece used for measuring the strain near the tip of an incision.

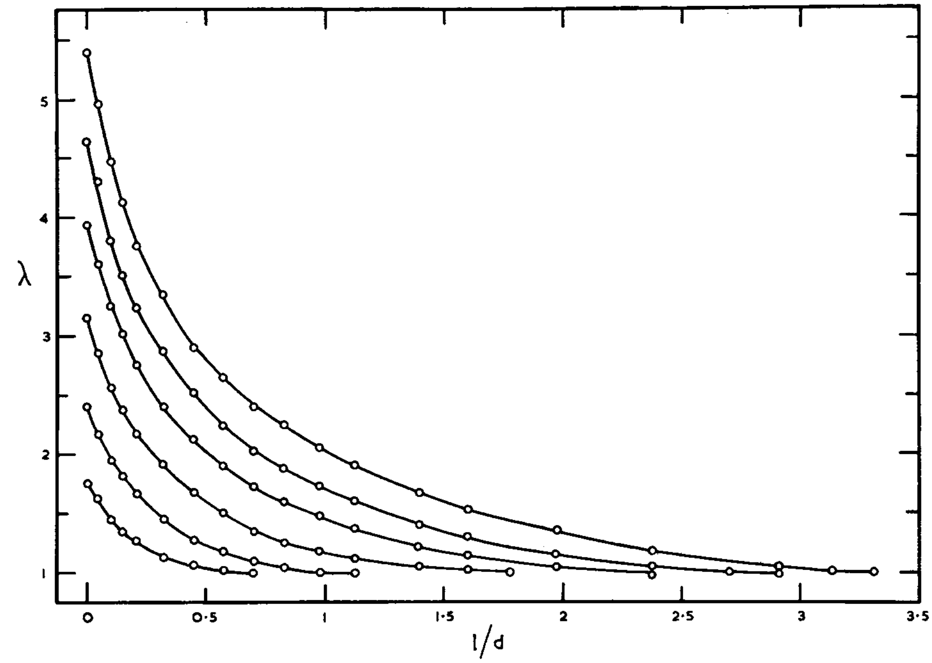

Fig. 2. Variation of the extension ratio λ with distance l from the tip of an incision; d is the diameter of the tip.

this is used in comparing the energy to initiate tearing with the work to break/unit volume measured in the tensile rupture tests. In using the time to break the same assumption as to the equivalence of uniform and nonuniform rates of extension is made as for continuous tearing.

EXPERIMENTAL

Measurements for Continuous Tearing

Measurements of the tearing energy for tears propagated at various rates were made according to the method which has been described in a previous paper.[4] The test pieces were of the general shape shown in Figure 1 but contained a simple cut in place of the large incision and were cut from vulcanized sheet of about $1^1/_2$ mm. thickness. The test pieces were extended at various uniform speeds in a tensometer, being immersed during extension in a water or alcohol bath maintained at the test temperature to $\pm 1°C$. The tearing energy and the rate of propagation were derived from the tearing force and the crosshead speed, respectively.[4] Except for certain instances pointed out in the description of the results, the measurements were made under conditions of stable tearing[4] where fluctuations in the tearing force and rate of propagation were small and random in nature. The experimental procedure under stable tearing conditions was as follows. Three or more test pieces were extended at each tensometer speed, and for each test piece the tearing force was noted at intervals once tearing had commenced; an average value for the tearing energy was then derived from the combined force readings. The rate of propagation, as derived from the tensometer crosshead speed, also represents an average value.

Measurements for Tearing at an Incision

Test pieces similar in shape to that shown in Figure 1 were used, these being cut from vulcanized sheet of about $1^1/_2$ mm. thickness. The test-pieces were 10 cm. by 4 cm. and contained an incision 7 cm. long with a semicircular tip of about 2 mm. diameter. The tip of the incision was formed with a circular cutter, and the diameter of the tip was measured with a travelling microscope.

Test pieces were extended at various uniform speeds in the tensometer described in the preceding paper.[6] The force on the test piece at the point of tearing, from which the energy to initiate tearing was derived,[1] and the time taken in extending the test piece to breaking point were obtained from the recorded force–distance curve. A water or alcohol bath was used for temperature control, as described in the preceding section.

Tensile Rupture Measurements

The work to break/unit volume was derived by graphical integration of the area under the load-extension curves as given in the preceding paper.[6] Mean values for the work to break/unit volume at each rate of extension were obtained from the results on the individual specimens.

Materials

The mixes and cures for the vulcanizates that were used have been described in the preceding paper. The vulcanizates were all compounded from GR-S (Polysar S), vulcanizate A being a gum compound and vulcanizates B and C filled compounds containing, respectively, HAF and SRF carbon blacks in the ratio of 50 parts per hundred of rubber. Several 30 cm. × 30 cm. sheets of each vulcanizate were prepared from a single mixing, sufficient for all the measurements. For experimental convenience separate sheets were used for each of the various sets of measurements.

RESULTS

Comparison of Measurements for Tensile Rupture and Tearing at an Incision

Mean values for the work to break/unit volume E measured in tensile rupture tests on the gum vulcanizate A at 25°C. are shown plotted against $1/t$ in Figure 3, t being the time taken in extending the specimens to breaking point. The values of E plotted are those given in Table II. The breaking time t was obtained from the rate of extension of the specimen, as given in Table II, and the corresponding mean value for the breaking extension as given in the preceding paper.[6] Values of T/d obtained in tear initiation tests on this vulcanizate at 25°C. are also shown in Figure 3, d being the diameter of the tip of the incision and T the energy to initiate tearing. The values of T/d have been plotted individually for each test piece. Similar data for the filled vulcanizate C at 25°C. are shown in Figure 4; the values for E in this case are those given in Table IV.

As will be seen from Figures 3 and 4, T/d and E are of comparable magnitude. The agreement, however, is not as close as would be expected from the theory leading to eq. (1). The probable reason for the discrepancy has been indicated by Thomas.[2] The apparent strength of the material would be expected to decrease as the size of specimen effectively tested is increased if the specimen contains flaws. As the size of specimen effectively tested in tearing at the incision was much smaller than the size of specimen used in the tensile rupture tests, T/d should accordingly be greater than E. It will be seen from Figures 3 and 4 that T/d is in fact greater than E; this has also been observed for natural rubber vulcanizates.[2]

T/d and E show the same variation with the breaking time t, within the experimental scatter. This suggests that the assumption that the strength of the material depends only on the average rate at which the material is extended to the breaking point is valid as a first approximation.

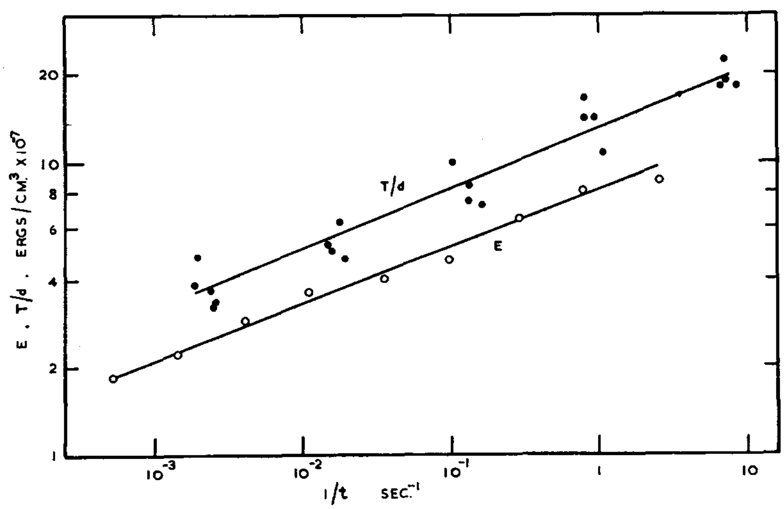

Fig. 3. Comparison of the work to break/unit volume E and the energy T to initiate tearing at an incision for vulcanizate A at 25°C. Here t is the time taken in extending the test piece to breaking point, and d is the diameter of the tip of the incision.

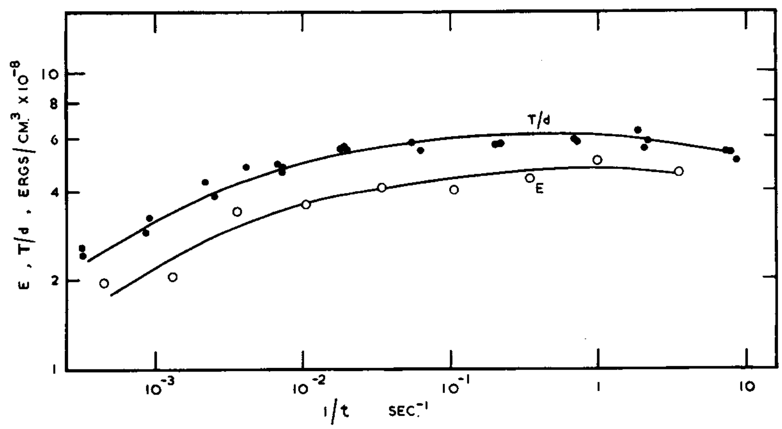

Fig. 4. Comparison of the work to break/unit volume E and the energy T to initiate tearing at an incision for vulcanizate C at 25°C. Here t is the time taken in extending the test piece to breaking point, and d is the diameter of the tip of the incision.

Comparison of Measurements for Tensile Rupture and Continuous Tearing

In the following comparisons of tear and tensile rupture measurements an attempt is made to account for the variation of the tearing energy with the rate of tear propagation in terms of the variation in the effective diameter of the tip of the tear and the variation in the strength of the material with rate of extension as obtained from the tensile rupture tests. Values for the tearing energy T and rate of tear propagation R have been derived by means of eqs. (1) and (3) from the values of the tensile work to break/unit volume E and rate of extension V, and these values are compared with the experimental tear data. The values for the effective diameter of the tip of the tear, d, used in eqs. (1) and (3) were chosen to give the best fit between the derived and experimental tear parameters. In some instances it was found that agreement could be obtained if d was assumed to be constant, but in others it was necessary to assume that d varied with the rate of tear propagation. Qualitative confirmation of the assumptions has been sought from the appearance of the torn surfaces.

The gum vulcanizate A provides instances where either the entire or the main contribution to the variation of the tearing energy with the rate of tear propagation is to be attributed to the variation of the work to break/unit volume with rate of extension. The filled vulcanizate B illustrates the other extreme, where the variation of the tearing energy with the rate of tear propagation is to be attributed largely to variation of the effective diameter of the tip of the tear. At certain test temperatures the tearing energy for the filled vulcanizate C shows a maximum value at a particular rate of tear propagation. Similar behavior is observed in the tensile rupture properties,[6] and the attempt to relate these maxima affords a critical test of eqs. (1) and (3).

Measurements on the Gum Vulcanizate A at 90 and 25°C.

Tear measurements made on the gum vulcanizate A at 90°C. are shown in Figure 5, together with values for the tearing energy and rate of tear propagation derived from the tensile rupture measurements of Table I for a value of 0.48 mm. for the effective diameter of the tip of the tear, d. The appearance of the torn surface at various rates of propagation is shown in Figure 6. As the roughness of the torn surface does not vary appreciably with the rate of propagation over the comparison range, the assumption that d is constant is reasonable. The derived and observed tear data are in

TABLE I
Tensile Rupture Measurements for Vulcanizate A at 90°C.

Rate of extension V, sec.$^{-1}$	1.4×10^{-3}	4.1×10^{-3}	1.4×10^{-2}	4.1×10^{-2}	1.4×10^{-1}	4.1×10^{-1}	1.4	4.1	14
Work to break/unit volume E, ergs/cm.^{3} $\times 10^{-6}$	5.7	6.0	7.8	7.3	11.1	11.6	18.4	22.3	21.5

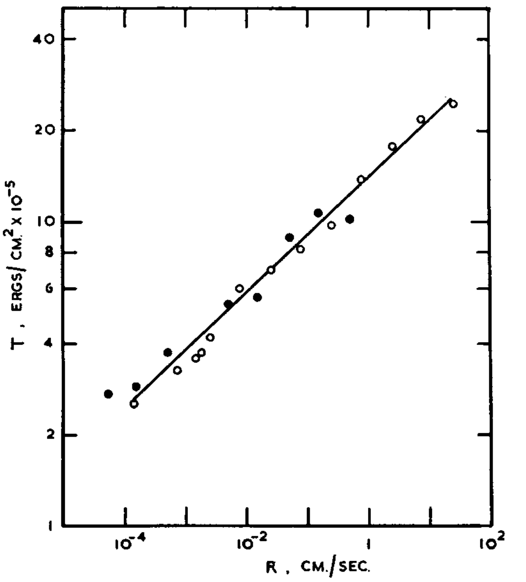

Fig. 5. Variation of the tearing energy T with rate of propagation R for vulcanizate A at 90°C.: (O) experimental values; (●) values derived from the tensile rupture measurements of Table I for a value for the effective diameter of the tip of the tear, d, of 0.48 mm.

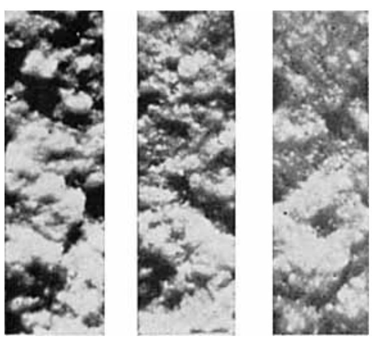

Fig. 6. Torn surfaces of vulcanizate A at 90°C. for rates of propagation (reading from left to right) of 10^{-3}, 2×10^{-2} and 1 cm./sec. The length of the surface shown is ca. 5 mm.

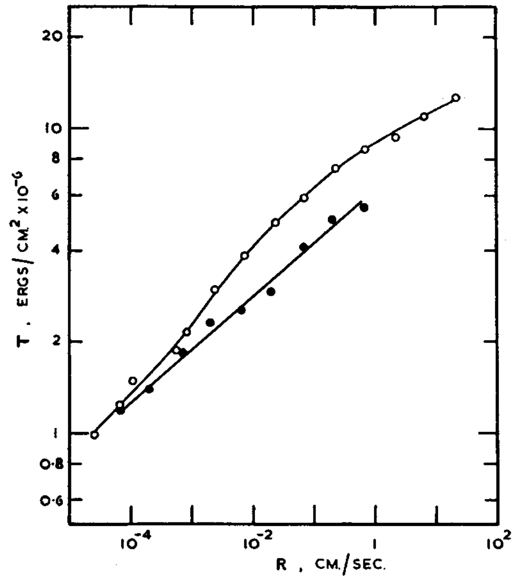

Fig. 7. Variation of the tearing energy T with rate of propagation R for vulcanizate A at 25°C.: (O) experimental values; (●) values derived from the tensile rupture measurements of Table II for a value for the effective diameter of the tip of the tear, d, of 0.64 mm.

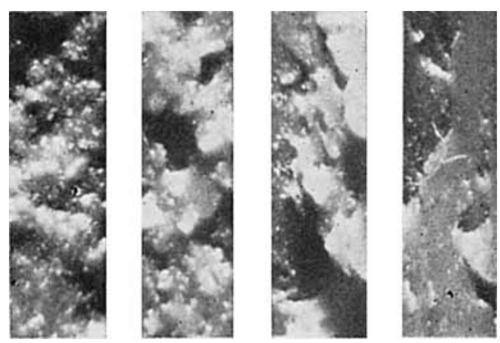

Fig. 8. Torn surfaces of vulcanizate A at 25°C. for rates of propagation (reading from left to right) of 10^{-4}, 2×10^{-3}, 2×10^{-1}, and 20 cm./sec. The length of the surfaces shown is ca. 5 mm.

agreement within the experimental scatter, and it appears, therefore, that the variation of the tearing energy with the rate of tear propagation can be accounted for, in the range for which the comparison has been made, in terms of the variation in the work to break/unit volume with the rate of extension of the material.

Tear measurements made on the gum vulcanizate A at 25°C. are shown in Figure 7, together with val-

TABLE II

Tensile Rupture Measurements and Related Data for Vulcanizate A at 25°C.

Rate of extension V, sec^{-1}	1.4×10^{-3}	4.1×10^{-3}	1.4×10^{-2}	4.1×10^{-2}	1.4×10^{-1}	4.1×10^{-1}	1.4	4.1	14
Work to break/unit volume E, ergs/cm.^{3} $\times 10^{-7}$	1.85	2.2	2.9	3.6	4.0	4.7	6.5	8.0	8.6
Effective diameter d, mm.	0.64	0.71	0.78	0.83	0.89	0.96	1.00	1.02	1.10
Rate of propagation R, cm./sec. (derived from V and d)	6.6×10^{-5}	2.2×10^{-4}	8.1×10^{-4}	2.6×10^{-3}	9.3×10^{-3}	3.0×10^{-2}	1×10^{-1}	3.3×10^{-1}	1.1

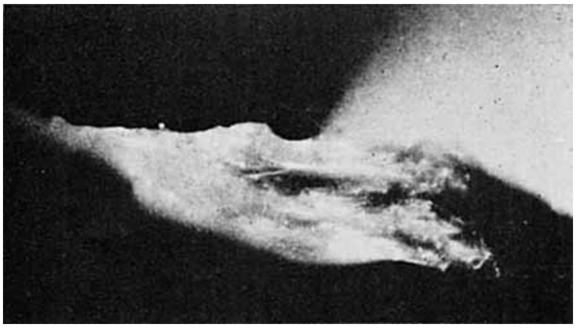

Fig. 9. Appearance of the tip of a tear in vulcanizate A. The tear was grown slowly (rate of propagation $<10^{-3}$ cm./sec.) at room temperature. The thickness of the test piece at the tip (in deformed state) is ca. 1 mm.

ues for the tearing energy and rate of propagation derived from the tensile rupture measurements given in Table II, a value for d of 0.64 mm. being used. The variation in the work to break/unit volume does not, in this instance, account entirely for the observed variation in the tearing energy, in contrast with the results at 90°C. (cf. also Fig. 3). Better agreement was obtained by assuming that d varies with the rate of propagation. The values assumed for d and the corresponding values for the rate of propagation derived from eq. (3) are shown in Table II. The assumed variation in d is not inconsistent with the observed change in the torn surface, as may be seen from Figure 8. At rates of propagation below about 10^{-3} cm./sec. the torn surface is similar to that at 90°C.; it becomes progressively more jagged in appearance as the rate of propagation is increased from 10^{-3} to about 1 cm./sec. and then becomes somewhat smoother as the rate of propagation is increased further. It appears, therefore, that the observed variation in the tearing energy may be qualitatively ascribed to variation in the work to break/unit volume and, to a lesser extent, to variation in the effective diameter of the tip of the tear.

At rates of propagation above 10^{-2} cm./sec. fairly large fluctuations in the tearing force and rate of propagation are observed during growth of the tear,[4,3] these being associated with the intermittent jaggedness of the torn surface. In these circumstances the values obtained for the tearing energy and rate of propagation depend to some extent on the averaging method. This, however, does not affect the qualitative conclusions drawn above.

The effective diameter of the tip of the tear at low rates of propagation at 25°C. should be comparable with that at 90°, as the torn surfaces are similar. The values obtained for the effective diameter, 0.64 and 0.48 mm., respectively, are in reasonably close agreement in view of the fact that the specimens used in the various sets of measurements were cut from different sheets of the vulcanizate. Under these conditions of tearing the torn surface has a granular appearance, as will be seen from Figures 6 and 8, the largest irregularities being an appreciable fraction of a millimeter in height or depth. The corresponding appearance of the tip of the growing tear is shown in Figure 9. It will be seen that there is no sharp line of demarcation between the ruptured surfaces; rupture occurs at points scattered over a relatively wide area around the tip.

Measurements on the Filled Vulcanizate B at 25°C.

Tear measurements for this vulcanizate at 25°C. are shown in Figure 10. Two levels of tearing energy are observed, a level as at A—associated with a greatly enlarged tip—and a level as in the region BC. The region BC will be considered first.

The appearance of the torn surface for various rates of propagation in the region BC is shown in Figure 11a. The torn surface has a small-scale roughness and larger-scale ridges and grooves with a height or depth of the order of a tenth of a millimeter. As the overall roughness of the surface does not vary appreciably with the rate of propagation, the effective diameter of the tip of the tear, d, may be expected to be substantially constant. Values for the tearing energy and rate of propaga-

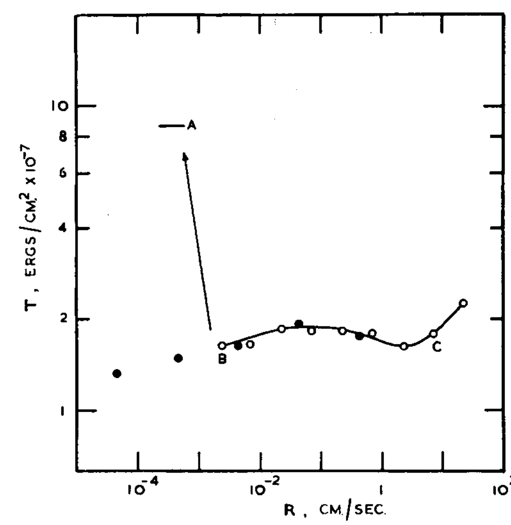

Fig. 10. Variation of the tearing energy T with rate of propagation R for vulcanizate B at 25°C.: (O) experimental values; (●) values derived from the tensile rupture measurements of Table III for a value for the effective diameter of the tip of the tear, d, of 0.40 mm.

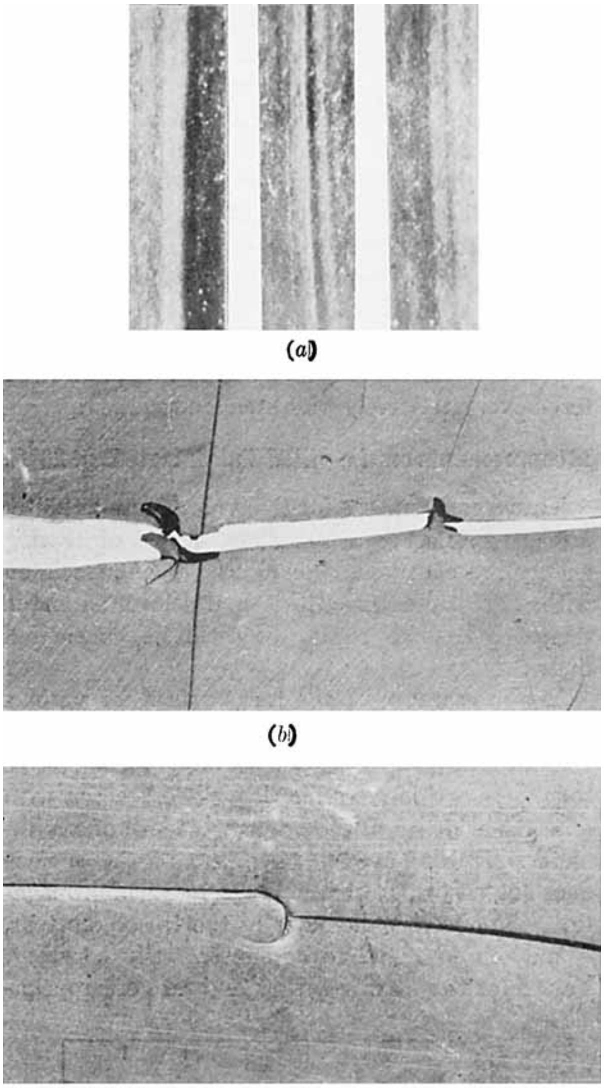

Fig. 11. Torn surfaces of vulcanizate B at 25°C. (*a*) for rates of propagation (reading from left to right) of 2×10^{-3}, 7×10^{-2}, and 7 cm./sec. The length of the surface shown is ca. 5 mm. (*b*) Knotty tear. (*c*) Semicircular knot.

TABLE III

Tensile Rupture Measurements for Vulcanizate B at 25°C.

Rate of extension V, sec.$^{-1}$	1.4×10^{-3}	1.4×10^{-2}	1.4×10^{-1}	1.4	14
Work to break/unit volume E, ergs/cm.^{3} $\times 10^{-8}$	3.4	3.7	4.1	4.8	4.3

tion derived by means of eqs. (1) and (3) from the tensile rupture measurements given in Table III for a value for d of 0.40 mm. are shown in Figure 10. These values are in good agreement with the experimental values for the region BC.

Knotty tearing occurs[5] if the rate of propagation is reduced below the point B shown in Figure 10, and the energy required for continuous propagation of the tear rises to a level as shown at A. Knotty tearing is a form of stick-slip tearing[5] in which an intermittent enlargement of the tip of the tear occurs, as shown in Figure 11*b*. The tearing energy as shown at A in Figure 10 is that measured at the point of catastrophic tearing from the enlarger tip or "knot," and the effective diameter d associated with this tearing energy is that appropriate to the knot. The values obtained for the effective diameter of knots in this vulcanizate with a value for E of 3.6×10^8 ergs/cm^3 in eq. (1) together with the appropriate value for the tearing energy were of the order of 2 mm., being comparable in magnitude with the lateral spread of the cracks forming the knot. In some instances, where the knot was close to semicircular form, quantitative comparison of the derived value of d with the measured diameter was possible. An example of such a knot is shown in figure 11*c;* the derived value for d was 2.4 mm. in this case, and the measured diameter was 1.8–2.0 mm.

Measurements on the Vulcanizate C at 25 and 0°C.

Tear measurements for the filled vulcanizate C at 25 and 0°C. are shown in Figures 12 and 13,

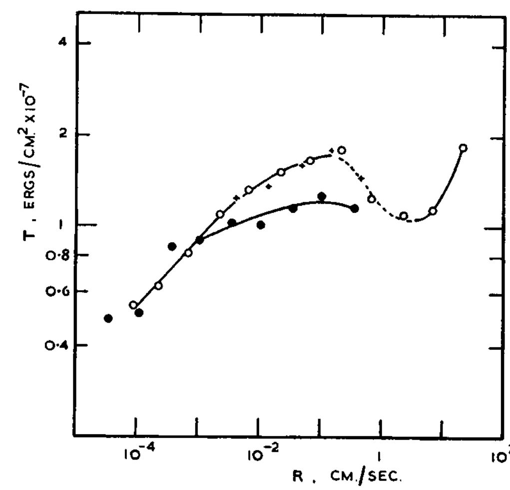

Fig. 12. Variation of the tearing energy T with rate of propagation R for vulcanizate C at 25°C.: (O) experimental values; (●) values derived from the tensile rupture measurements of Table IV for a value for the effective diameter of the tip of the tear, d, of 0.25 mm.; (+) values derived from the tensile rupture measurements for a value of d which varies as shown in Table IV.

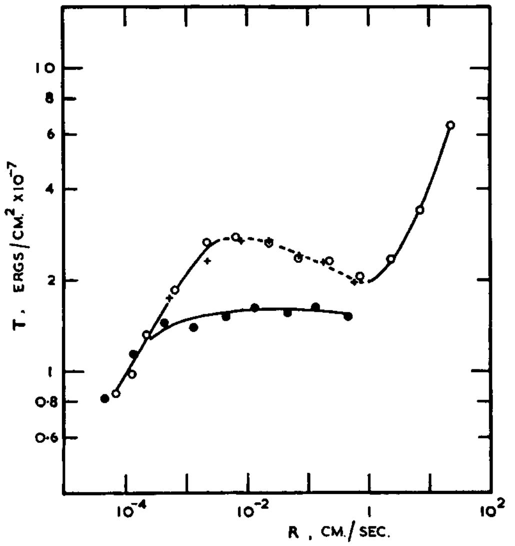

Fig. 13. Variation of the tearing energy T with rate of propagation R for vulcanizate C at 0°C.: (O) experimental values; (●) values derived from the tensile rupture measurements of Table V for a value for the effective diameter of the tear, d, of 0.32 mm.; (+) values derived from the tensile rupture measurements for a value of d which varies as shown in Table V.

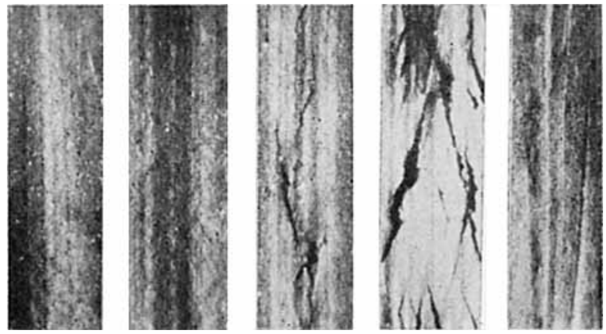

Fig. 14. Torn surfaces of vulcanizate C at 25°C. for rates of propagation (reading from left to right) of 10^{-4}, 2×10^{-3}, 2×10^{-2}, 2×10^{-1}, and 2 cm./sec. The length of the surface shown is ca. 5 mm.

respectively. The curves of tearing energy against rate of tear propagation at these temperatures show similar features, but the maximum in the tearing energy occurs at a lower rate of propagation at 0° than at 25°C. The broken lines denote stick-slip tearing, and the measurements in this region are to be regarded as providing a qualitative, rather than a strictly quantitative, representation of the variation of the tearing energy with the rate of tear propagation.[4,5] The method of measurement for stick–slip tearing conditions has been described previously.[4,5]

As the roughness of the torn surface at these temperatures varies somewhat with the rate of tear propagation, variation in the effective diameter of the tip of the tear, d, would be expected but, to illustrate the contribution from the variation in the work to break/unit volume, d is initially treated as a constant. Values for the tearing energy and rate of tear propagation derived from the tensile rupture measurements of Tables IV and V with values for d of 0.25 and 0.32 mm. at 25 and 0°C., respectively, are shown in Figures 12 and 13. These derived

TABLE IV

Tensile Rupture Measurements and Related Data for Vulcanizate C at 25°C.

Rate of extension V, sec.$^{-1}$	1.9×10^{-3}	5.7×10^{-3}	1.9×10^{-2}	5.7×10^{-2}	1.9×10^{-1}	5.7×10^{-1}	1.9	5.7	19
Work to break/unit volume E, ergs/cm^3 $\times 10^{-8}$	1.9	2.1	3.4	3.6	4.1	4.0	4.5	5.0	4.6
Effective diameter d, mm.	0.25	0.25	0.25	0.26	0.30	0.34	0.35	0.36	0.32
Rate of propagation R, cm./sec. (derived from V and d)	3.6×10^{-5}	1.1×10^{-4}	3.6×10^{-4}	1.1×10^{-3}	4.4×10^{-3}	1.4×10^{-2}	5.0×10^{-2}	1.5×10^{-1}	4.6×10^{-1}

TABLE V

Tensile Rupture Measurements and Related Data for Vulcanizate C at 0°C.

Rate of extension V, sec.$^{-1}$	1.9×10^{-3}	5.7×10^{-3}	1.9×10^{-2}	5.7×10^{-2}	1.9×10^{-1}	5.7×10^{-1}	1.9	5.7	19
Work to break/unit volume E, ergs/cm.^{3} $\times 10^{-8}$	2.6	3.6	4.6	4.4	4.7	5.1	4.9	5.1	4.8
Effective diameter d, mm.	0.32	0.32	0.38	0.52	0.56	0.52	0.49	0.45	0.41
Rate of propagation R, cm./sec. (derived from V and d)	4.6×10^{-5}	1.3×10^{-4}	5.5×10^{-4}	2.2×10^{-3}	8.1×10^{-3}	2.2×10^{-2}	7.1×10^{-2}	1.9×10^{-1}	5.9×10^{-1}

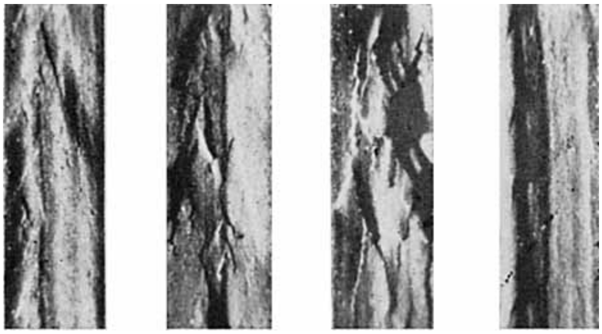

Fig. 15. Torn surface of vulcanizate C at 0°C. for rates of propagation (reading from left to right) of 10^{-4}, 7×10^{-4}, 7×10^{-3}, and 7×10^{-1} cm./sec. The length of the surface shown is ca. 5 mm.

values show qualitatively the same trends as the experimental tear data. Values for the tearing energy and rate of tear propagation derived on the assumption that d varies with the rate of propagation are also shown in Figures 12 and 13, and these give a reasonably good representation of the experimental tear data. The values assumed for d and the corresponding values derived for the rate of tear propagation are shown in Tables IV and V. As will be seen from the torn surfaces shown in Figures 14 and 15, the assumed variation in d with the rate of tear propagation is, in each case, qualitatively consistent with the variation in the roughness of the torn surfaces, the roughness being greatest at the rate of propagation for which the tearing energy is a maximum. Furthermore, the use of higher values of d at 0° than at 25°C. is consistent with the greater roughness of the torn surfaces at 0°C.

It is apparent from Figure 12 and Table IV that in the above representation the tearing energy maximum at 25°C. is associated both with a maximum in the effective diameter of the tip of the tear and with a maximum in the work to break/unit volume for the material (also with a maximum in tensile strength[6]). It will be seen from Figure 13 and Table V that, at 0°C. also, the tearing energy maximum is associated with a maximum in the effective diameter of the tip of the tear. Although in this case there is not a well-defined maximum in the work to break/unit volume, there is a well-defined maximum in the tensile strength[6] at a rate of extension in the neighborhood of 0.57 sec.^{-1}. This rate of extension, it will be seen from Table V, is close to that at which d is a maximum. Hence, in the above representation, the tearing energy maximum at 0°C. is also closely associated with a maximum in tensile strength.

DISCUSSION

The comparisons of tear and tensile rupture indicate that the tearing energy for low and moderate rates of propagation of the tear can be plausibly related to the strength of the material as measured in tensile rupture tests on the assumption of an effective diameter for the tip of the tear. It has been seen that, apart from knotty tearing, values for the effective diameter d of a few tenths of a millimeter were required to fit the tear and tensile rupture measurements. Such values are reasonable, as judged by the irregularities in the torn surfaces. The values for d refer to tears in rubber sheet of about $1^1/_2$ mm. thickness. Smaller values of d would be expected for thinner sheets, as the irregularities in the torn surface would be expected to diminish as the thickness of the sheet is decreased. In the case of knotty tearing, where the tip of the tear tends to develop a regular form due to the anisotropy of the material in the stretched state,[5] the value assumed for d, it has been seen, can be confirmed by direct measurement of the tip diameter.

It was assumed in applying eq. (1) to continuous tearing that (a) the rubber around the tip of the tear is in simple extension and also that (b) the strength of a tensile rupture specimen is the same as that of the much smaller specimen effectively tested in tearing. The first assumption would not be expected to be strictly valid where the irregularities at the tip of the tear are small in comparison with the thickness of the test piece. It is not certain what the effect would be on the value obtained for the effective diameter of the tip of the tear. It has previously been indicated that the second assumption may not be strictly valid, i.e., the apparent strength of the material may decrease as the size of the specimen effectively tested is increased. The effect would be to give an exaggerated value for the effective diameter of the tip of the tear. An indication of the probable magnitude of the exaggeration may be obtained from Figures 3 and 4, where measurements for tensile rupture and tearing at an incision are compared.

It has been supposed, in applying eq. (1) to continuous tearing, that dissipation of energy is confined to the material around the tip of the tear which has been brought to the breaking point or to high extensions close to the breaking point. Additional dissipation of energy will occur, however, in regions adjacent to the tip where, as the tear advances, the material is subjected to moderate extensions and is then relaxed. This additional dissipation of energy may well be considerable at high rates of propagation where rapid deformation occurs. Accordingly, eq. (1) would not be expected to be applicable at high rates of propagation without the addition of an extra term. Also, eq. (3) would not be expected to be applicable under these conditions, as has been indicated previously. Some additional dissipation of energy may occur as envisaged above in filled vulcanizates even at low rates of propagation. The effect would be to give a value for the effective diameter of the tip of the tear which was rather high in comparison with the roughness of the torn surface.

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Synopsis

The energy to initiate tearing at an incision with a tip of semicircular form was shown in a previous paper to be approximately equal to *Ed, E* being the work to break/unit volume as measured in a tensile rupture test and *d* the diameter of the tip of the incision. In the present paper this relation is used to compare the effects of the speed of test on tear and tensile rupture measurements. It is shown that the variation of the work to break/unit volume with the speed of test adequately accounts for the effect of the speed of test on the energy to initiate tearing at incisions with tips of semi-circular form. It is assumed that the relation applies also in continuous tearing, *d* being in this case the effective diameter of the tip of the tear, and it is shown that the variation of the tearing energy with the rate of tear propagation, at low and moderate rates of propagation, may be plausibly accounted for in terms of the variation of the work to break/unit volume with the speed of test and variation of the effective diameter of the tip of the tear, *d*. Values of *d* of a few tenths of a millimeter were generally required to fit the tear and tensile rupture measurements, the values being, as expected, comparable in magnitude with the irregularities in the torn surfaces. It is shown that in certain instances the values assumed for *d* may be confirmed by direct measurement of the diameter of the tip of the tear.

Résumé

Dans une communication antérieure il a été montré que l'énergie nécessaire pour amorcer une déchirure à une incision de forme semi-circulaire est approximativement égale à *Ed* où *E* est le travail de rupture par unité de volume mesuré par un test de rupture à l'étirement et *d* est le diamètre de la pointe circulaire de l'incision. Dans la présente communication il est fait usage de cette relation pour comparer les effets de la vitesse du test sur les mesures de déchirure et de rupture à l'étirement. Il a été montré que la variation du travail de rupture par unité de volume en fonction de la vitesse du test concorde entièrement avec l'influence de la vitesse du test sur l'énergie nécessaire à l'amorçage d'une déchirure à une incision avec pointe de forme semi-circulaire. On a admis que la relation s'applique également au déchirement continu, *d* étant dans ce cas le diamètre effectif de la pointe du déchirement. Il a été montré que la variation de l'energie de déchirement en fonction de la vitesse de propagation de la déchirure, aux faibles et moyennes valeurs de cette vitesse, peut être expliquée de façon plausible d'après la variation du travail de rupture par unité de volume en fonction de la vitesse du test et d'après la variation du diamètre effectif *d* de la pointe de la déchirure. Des valeurs de *d* de quelques dixièmes de millimètre sont généralement requises d'après les mesures de déchirement et de rupture par étirement. Ces valeurs sont, comme, il fallait s'y attendre, aux dimensions des irrégularités des surfaces déchirées. Il a été montré que dans certains cas les valeurs admise pour *d* peuvent être confirmées par mesure directe du diamètre de la pointe de la déchirure.

Zusammenfassung

In einer früheren Veröffentlichung wurde gezeigt, dass die zur Einleitung des Zerreissens an einem Einschnitt mit halbkreisförmiger Spitze notwendige Energie angenähert gleich *Ed* ist, wo *E* die Brucharbeit/Volumseinheit, wie sie bei einem Zug-Bruchversuch gemessen wird, und *d* der Durchmesser der Einschnittspitze ist. In der vorliegenden Mitteilung wird diese Beziehung zum Vergleich des Einflusses der Geschwindigkeit des Testes auf die Reiss- und Zug-Bruchmessungen benützt. Es wird gezeigt, dass die Abhängigkeit der Brucharbeit/Volumseinheit von der Testgeschwindigkeit in angemessener Weise den Einfluss der Testgeschwindigkeit auf die zur Einleitung des Zerreissens an Einschnitten mit halbkreisförmiger Spitze notwendige Energie erklären kann. Es wird angenommen, dass die Beziehung auch bei kontinuierlichem Reissen anwendbar ist, wobei *d* in diesem Fall der effektive Durchmesser der Spitze des Risses ist. Es wird gezeigt, dass die Abhängigkeit der Reissenergie von der Wachstumsgeschwindigkeit des Risses bei niedriger und mässig grosser Wachstumsgeschwindigkeit in plausibler Weise als Funktion der Abhängigkeit der Brucharbeit/Volumseinheit von der Testgeschwindigkeit und der Abhängigkeit des effektiven Durchmessers der Rissspitze, *d*, dargestellt werden kann. Zur quantitativen Wiedergabe der Reiss- und Zug-Bruchmessungen sind *d*-Werte von einigen Zehntelmillimeter erforderlich, was, wie zu erwarten, mit der Grösse der Unregelmässigkeit der Reissflächen vergleichbar ist. Es wird gezeigt, dass in gewissen Fällen die für *d* angenommenen Werte durch direkte Messung des Durchmessers der Rissspitze bestätigt werden können.

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