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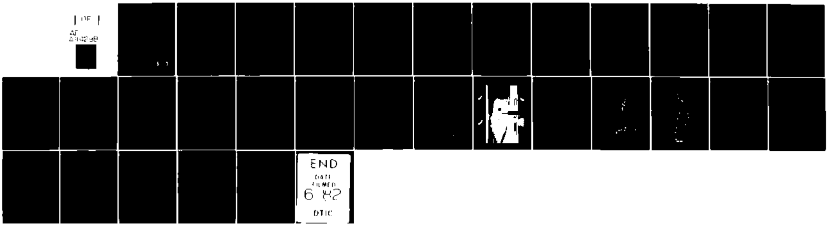

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CRACK VELOCITIES IN NATURAL RUBBER

by

A. N. Gent and P. Marteny

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Akron, Ohio 44325

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Measurements are reported of the limiting velocity of a running crack in biaxially stretched sheets of unfilled and carbon-black-filled natural rubber. The crack velocity was found to increase with the cleavage strain e_y and also with the strain e_x parallel to the direction of tearing, reaching values of over 100 m/s at the highest strain levels employed. These crack velocities are shown to be close to those predicted by Mott's theory, i.e., about one-third of the velocity of

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20. (continued)

sound, when a strong strain-dependence is recognized for the velocity of sound in rubber.

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I. Introduction

The maximum velocity $\underline{v_c}$ of a running crack has been shown by Mott to be related to the velocity $\underline{v_s}$ of sound (1). Roberts and Wells computed the ratio $\underline{v_c/v_s}$ to be 0.38 for a material having a value of Poisson's ratio of 0.25(2). Reported values of $\underline{v_c}$ and $\underline{v_s}$, although relatively few in number, are in reasonably good agreement with this prediction.

For highly-elastic materials, however, the agreement is less satisfactory. Mason found $\underline{v_c/v_s}$ to be about 0.3 for a vulcanized SBR elastomer and about 0.03 for a vulcanized natural rubber (3). The surprisingly low value for natural rubber was attributed to highly anisotropic elastic behavior at high strains, rendering invalid the theoretical treatments of Mott, and Roberts and Wells, which assumed small-strain isotropic behavior. Recent studies by Stevenson and Thomas of the velocities of crack propagation in bursting rubber balloons led to estimates of the ratio $\underline{v_c/v_s}$ of about 3.2 for natural rubber, about two orders of magnitude greater than Mason's result (4).

No other studies of high-speed crack velocities in rubber are known to the present authors. Measurements have therefore been carried out for carbon-black-filled and unfilled natural rubber sheets, held under various states of strain. They are reported here and compared with recent measurements of the velocity $\underline{v_s}$ of sound in stretched rubber (5).

2. Experimental details

(i) Materials used

Rubber sheets were prepared using the mix formulations and vulcanization conditions given in the Appendix. Test strips were cut from the sheets about 250 mm long, 20 mm wide and 0.5 mm thick. Some samples of similar dimensions were prepared in a special mold, to give thickened edges along the 250 mm sides for ease of clamping. A grid was painted on one surface of the test strips to allow strains to be measured.

(ii) Biaxial straining

The test strip was first stretched along its length, denoted the $\underline{x}$ direction, to the required strain $\underline{e_x}$. Two parallel rigid clamps, 150 mm long, were then applied to the strip edges so that a section of the strip, about 150 mm long and 10 mm wide, was secured between them in the stretched state. When these clamps were fastened, the original stretching force was released. The specimen then remained stretched in its length direction (except for small regions at the ends), because the clamps along each side prevented it from returning to the unstrained state.

The clamps were then attached to a loading device, arranged to pull them apart in the y direction and thus impose on the rubber strip an additional strain e_y in a direction perpendicular to the first. The strain e_y was always made greater than the strain e_x so that a crack initiated in the center of the strip would run in the long x-direction rather then in the short y-direction and would therefore be more easily studied.

Measurements were made of the amount of work required to stretch the rubber sheet in the y -direction to the strain e_y. On dividing by the volume of rubber, this gave the strain energy density W for a particular combination of strains e_x, e_y that would be released by a crack running in the x -direction. (It is assumed that the original work of imposing the strain e_x is not released by such a crack). The amount of energy released by such a crack, per unit area of material torn through, is then given by

$$T = Wh_o \qquad (1)$$

where h_o denotes the strip width in the y direction between the clamps, when the force in this direction is zero (6). The tear energy *T* has been shown to be the parameter governing slow crack growth in elastomeric materials under varied loading conditions (7-10). Cracks do not propagate unless *T* exceeds a well-defined critical value. Above this value, the rate of propagation appears to depend solely upon the magnitude of *T*. The same concept has been applied to other materials. *T* is termed the strain energy release rate and its critical value, sometimes denoted G_c, is termed the fracture energy of the material. We examine below whether the magnitude of *T* governs the velocity of high-speed cracks.

(iii)Measuring the crack velocity

A crack was initiated in the center of a biaxially-stretched strip by piercing it with a needle point that had been filed to resemble a spearhead in order to help guide the crack in the *x*-direction. As the crack grew it permitted a light beam from a laser source to illuminate a photo-sensitive trigger and thus to set off a series of three flashtubes, Figure 1, giving a triple exposure of the propagating crack on a photographic film. The same arrangement was employed previously for determining velocities of free retraction of stretched rubber strips, and has been described more fully in that connection (5).

A representative photograph is shown in Figure 2. From the distance moved by the crack tip between successive exposures, and the measured time interval between flashes, mean values of the velocity $\underline{v}_c$ of crack propagation were determined. No indication was found either of acceleration or deceleration of the crack over the distances studied, about 5 cm of growth on each side. This conclusion is supported by the observations of Mason (3) and Stevenson and Thomas (4).

3. Results and discussion

(i) The relation between crack velocity and tear energy

As will be discussed in more detail later, measured crack velocities were found to depend strongly upon the levels of strain $\underline{e}_x$ and $\underline{e}_y$. If $\underline{e}_y$ was not sufficiently large, then the crack did not propagate at all. Above the critical value of $\underline{e}_y$, the crack grew at rates between about 5 and 100 m/s, depending upon the strains imposed. The first question to consider, then, is whether the crack velocity depends solely upon the available energy $\underline{T}$, or whether it is a function of the local state of strain only. These parameters can be adjusted separately with the specimens used in the present experiments. By varying the width $\underline{h}_o$ of the strip between the clamps, the magnitude of $\underline{T}$

can be changed even when the strain levels and the strain energy density W are held constant, equation 1.

Measurements were made of the crack velocity v_c in strips of unfilled natural rubber of various widths h_o ranging between 2 and 15 mm, when the strips were stretched to $e_x = 1$ and $e_y = 3$. At these strain levels, $W = 3\ MJ/m^3$. The results are shown in Figure 3. Until $h_o = 3$ mm, the crack velocity was effectively zero. From equation 1, the critical tear energy T for a crack to propagate at all is thus about 9 kJ/m^2. Measurements at other strain levels confirmed the validity of this tear energy criterion for any crack growth to occur. Above this energy level, as shown in Figure 3, the crack velocity increased rapidly with incresing width h_o of the strip, to reach an upper value of about 53 m/s. It then became quite independent of the strip width, i.e., of the tear energy T. Thus, it may be concluded that whereas a tear energy criterion governs the onset of fracture and probably governs the rate of slow-speed cracks, the maximum crack velocity is independent of the available energy for tearing. It depends strongly upon the imposed strains, however, as discussed below.

(ii) Effect of imposed strains upon the maximum crack velocity

Measured crack velocities v_c are plotted as a function of the imposed strains in Figures 4 and 5. For the unfilled material A, v_c increases with increasing strain e_y. Moreover, at any value of e_y, v_c increses markedly with e_x. Apparently the material tears much more rapidly when it is held somewhat stretched in the direction of the running crack. A pronounced reduction in tear strength for a sample held stretched in the tear direction has been noted previously (11).

Similar behavior was shown by the carbon-black-filled material B, Figure 5. However, relatively slow crack growth was observed for this material over a range of strains e_y from about 1.2 to 2.0, when the strain e_x was small or zero. Over this range of strains the crack velocity was anomalously low, only about 3 m/s. On examining the torn surfaces they were relatively smooth and structureless at a magnification of 300x, for all strain conditions, whether the crack had grown at about 3 m/s or at a much higher velocity. The anomalously-low rates of tearing at low strains cannot therefore be ascribed to a change in the geometry of tearing and must reflect an intrinsic resistance to fracture at high speeds, presumably from an energy-dissipation mechanism in material B that is not present in material A. One such process would be the detachment of rubber from filler particles under the high stresses set up at the crack tip.

(iii)Comparison with Mott's theory

As shown in Figures 4 and 5 the crack velocity increased rapidly with increasing strain for both the unfilled and carbon-black-filled materials, reaching values of over 100 m/s at the highest strain levels employed. In experiments with a bursting balloon, where the strain $\underline{e_y}$ $(=\underline{e_x})$ ranged from 1.3 to 4.0 strain units, Stevenson and Thomas reported even higher velocities $\underline{v_c}$ of 130 to 285 m/s (4). These values are now compared with the predictions of Mott's theory.

By including kinetic energy in the relation for energy changes during propagation of a crack, Mott showed that the maximum crack velocity should be proportional to the velocity $\underline{v_s}$ of a stress pulse in the material (1). Roberts and Wells determined the constant of proportionality to be a rather complicated function of Poisson's ratio, taking the approximate value of 0.38 when Poisson's ratio is 0.25 (2). As described elsewhere, this constant becomes 0.3 when Poisson's ratio is taken as 0.5, the appropriate value for virtually incompressible materials like rubber (6).

Now the velocity v_s of a stress pulse in rubber is strongly dependent upon the state of strain (5). Some representative values are given in Table 1. Values of the maximum crack velocity v_c, calculated from measured values of v_s on the assumption that Mott's relation holds for stretched rubber, are given in Table 1. They are also shown in Figures 4 and 5 as full curves, for comparison with the experimentally-determined values of v_c. They are seen to be in reasonably good agreement with the highest crack velocities measured, i.e., those observed when the strains e_x and e_y were both relatively large. Moreover, the measured values increase rapidly with the imposed strain e_y, in good agreement with the predicted relations.

Thus, for both unfilled and carbon-black-filled samples of natural rubber, the maximum observed velocities of crack propagation are in good agreement with the relation

$$v_c = 0.3\ v_s \qquad (2)$$

when the velocity v_s is determined at an appropriate state of strain. Because v_s is strongly dependent upon the state of strain, the maximum crack velocity is predicted to increase from about 20 m/s to about 200 m/s for the unfilled material A over the range of strains $e_y = 1$ to $e_y = 4.5$, and from about 90 m/s to about 220 m/s for the carbon-black-filled material B over the range of strains $e_y = 1$ to $e_y = 2$. The measured values are in reasonably good agreement with these predictions.

It should be noted that no allowance has been made for possible changes in the velocity v_s when a strain e_x is imposed perpendicular to the direction of travel of the stress pulse. The predicted relations are based solely on values of v_s determined for strips in a state of simple extension, i.e., with $e_x = e_y^{-\frac{1}{2}}$. A large effect of strains e_x imposed in a perpendicular direction is not expected for the velocities v_s, however.

(iv) Comparison with other work

Crack tip velocities reported by Stevenson and Thomas (4) are given in Table 1. They are seen to be in reasonable agreement with values calculated for a carbon-black-filled natural rubber material B, using the measured velocity of sound at the particular imposed strain. As Stevenson and Thomas pointed out, the velocity of sound at small strains is clearly far too low to account for their observed crack velocities and those reported here. They were not aware that much higher sound velocities are encountered at moderately high strains, and attributed the high crack velocities to special conditions set up at the crack tip itself. This assumption does not now seem to be necessary because the observed crack velocities can be accounted for solely in terms of the measured strain dependence of the velocity of a stress pulse in rubber.

4. Conclusions

The velocity of crack propagation in biaxially-strained sheets of natural rubber is an increasing function of the biaxial strains $\underline{e}_x$ and $\underline{e}_y$. Below a critical value of the cleavage strain $\underline{e}_y$, which depends on the strip width, no crack growth occurred. These critical conditions correspond to an energy requirement for fracture of about 5-10 kJ/m^2 for an unfilled natural rubber vulcanizate A and about 15-20 J/m^2 for a carbon-black-filled natural rubber vulcanizate B.

For the filled material, cracks grew at relatively low velocities, about 3 m/s for a range of imposed strains above the critical level and then the velocity increased rapidly at higher strains. In contrast, cracks grew rapidly in the unfilled material once the cleavage strain was high enough to permit tearing to occur at all. The velocities of high-speed cracks were found to be independent of the available energy for fracture and depended solely upon the state of strain.

Values of maximum velocity v_c were calculated from measured values of the velocity v_s of sound at various imposed strains. Agreement with the observed maximum crack velocities was surprisingly good, both in general magnitude and in the strong dependence upon the imposed strain, for both materials examined.

Acknowledgements

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Appendix

The mix formulations are given below in parts by weight.

Unfilled natural rubber (A):

Natural rubber (SMR-5L), 100; zinc oxide, 5; stearic acid, 2; phenyl-2-naphthylamine, 1; N-cyclohexyl-2-benzothiazyl sulfenamide, 0.6; sulfur, 2.5.

Carbon-black-filled natural rubber (B):

As for A, with the addition of N330 carbon black (Vulcan 3, Cabot Corporation), 50.

The compounds were vulcanized in the form of thin sheets by heating them in a press for 24 min at 150°C.

Table 1. Representative values of the velocity $\underline{v_s}$ of a stress pulse, taken from reference (5), and crack velocities $\underline{v_c}$.

$\underline{e_y}$	$\underline{v_s}$ (m/s)	$\underline{v_c}$ (calc. from equation 2) (m/s)	$\underline{v_c}$ from [reference (4)] (m/s)
		Unfilled material A	
1.3	75	22.5	133
2.0	90	27	---
2.7	180	57	230
3.0	250	75	---
4.0	400	120	285
		Carbon-black-filled material B	
1.3	380	123	133
2.0	720	216	---
2.7	>900	>270	230
3.0	---	---	---
4.0	---	---	285

Figure Captions

Figure 1. Method of measuring the velocity of a crack in a biaxially-strained rubber strip.

Figure 2. Triple-exposure photograph of a growing crack in material B. $e_x = 0.4$, $e_y = 2.3$.

Figure 3. Crack velocity v_c in strips of varying unstrained width h_o. Material A; $e_x = 1$, $e_y = 3$.

Figure 4. Crack velocity v_c in biaxially-strained sheets of material A. The vertical dotted line represents the threshold strain below which the crack did not grow at all. The full curve represents the predictions of Mott's theory: $v_c = 0.3\ v_s$, using values of v_s appropriate to the strain e_y.

Figure 5. Crack velocity v_c in biaxially-strained sheets of material B. The vertical dotted line represents the threshold strain below which the crack did not grow at all. The full curve represents the predictions of Mott's theory: $v_c = 0.3v_s$, using values of v_s appropriate to the strain e_y.

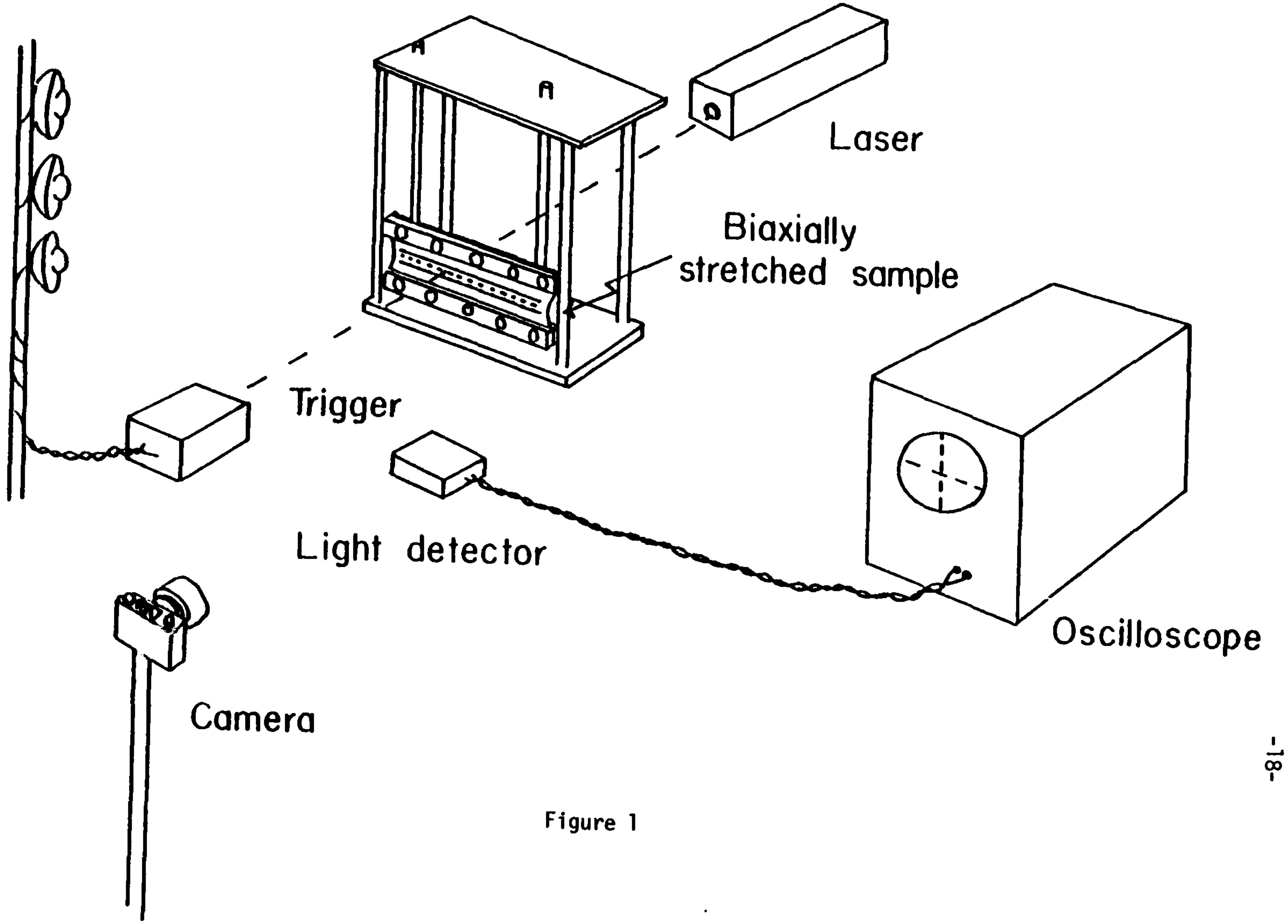
A
A
Laser
Biaxially stretched sample
Trigger
Light detector
Oscilloscope
Camera

Figure 1

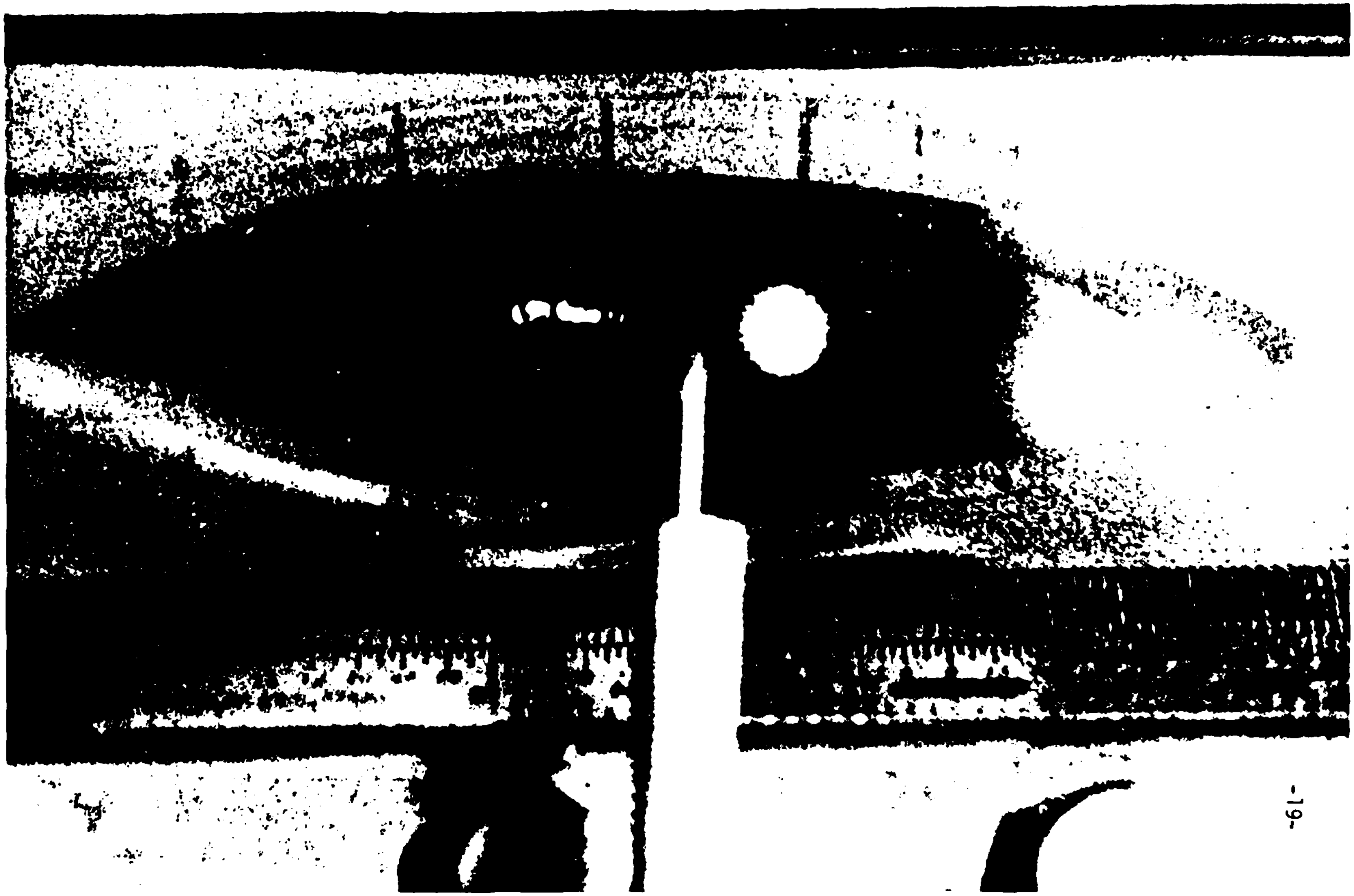

Figure 2

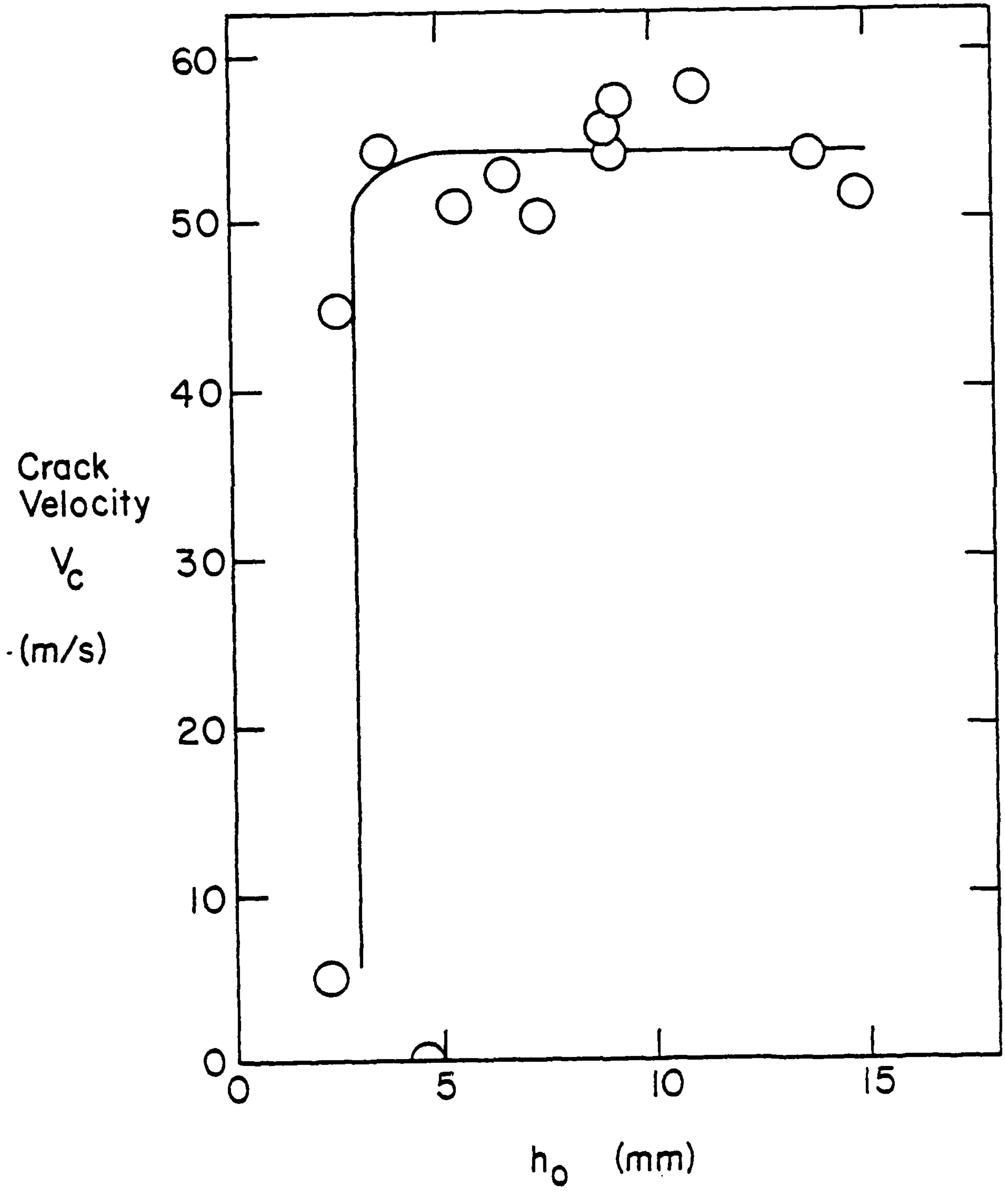

Figure 3

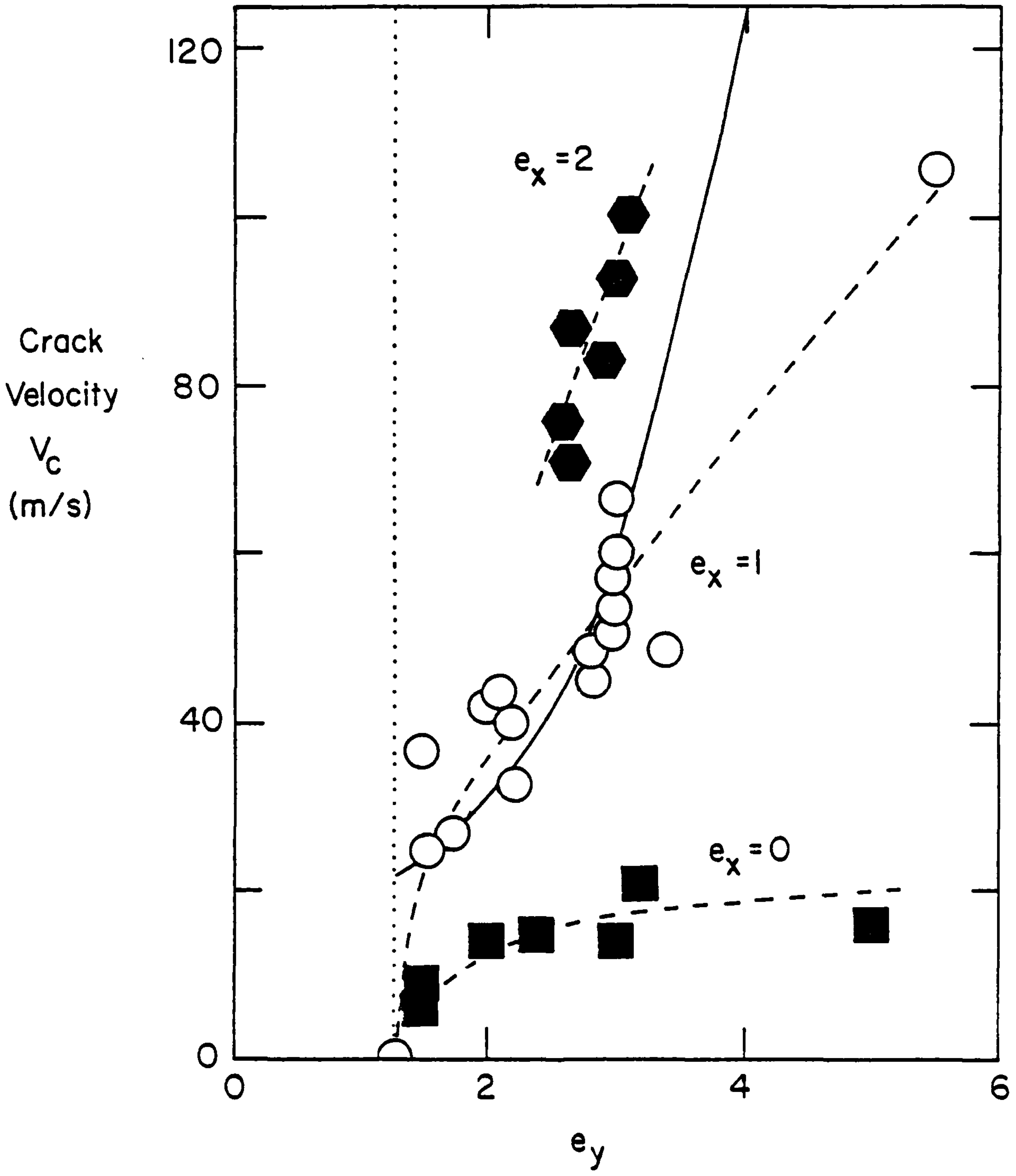

Figure 4

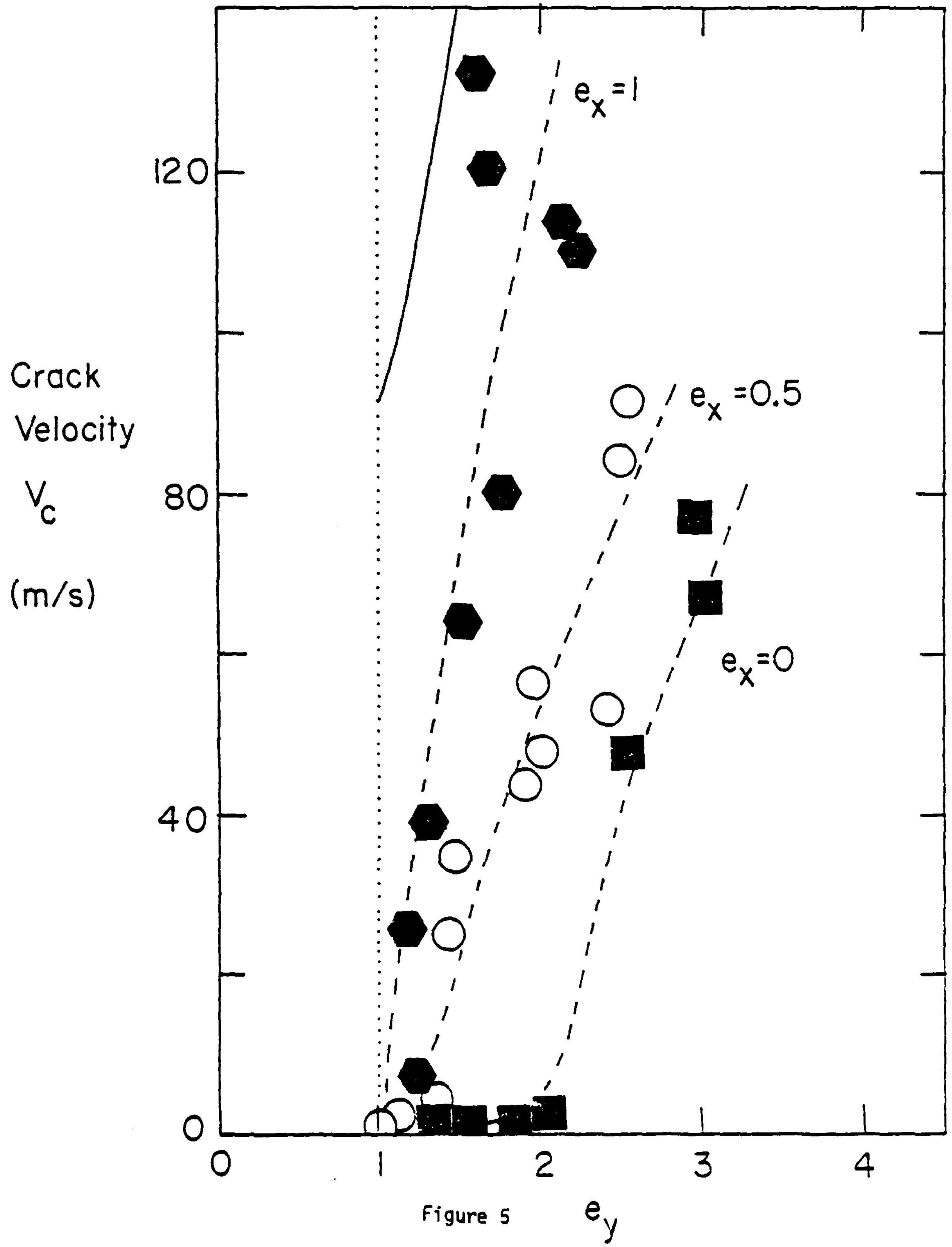

Figure 5

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