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Effect of crack layer on dynamic crack propagation behaviour in polystyrene

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Dynamic crack propagation in thin, edge-notched polystyrene specimens was studied by the method of dynamic caustics. During crack propagation, an intensive zone of crazing surrounds and precedes the propagating crack. Therefore, an active zone ahead of the crack tip is developed. This active zone is related to the velocity of crack propagation and the strain rate of loading. The velocity of the crack and the stress intensity factor, K_I, or the energy release rate, G_I, were strongly influenced by the development of the active zone at the crack tip.

1. Introduction

Fatigue crack propagation and damage in thin, single edge-notched polystyrene specimens was studied by Botsis and co-workers [1–3]. According to their studies, an intensive zone of crazing surrounds and precedes the propagating crack. The system of the crack and craze zone constitute a crack layer, part of which, ahead of the crack tip where crazing accumulates prior to crack layer growth, is called the active zone. A schematic drawing of a rectilinear crack layer is shown in Fig. 1 [2]. The area ahead of the crack tip, limited by the trailing and leading edges, is defined as the active zone. Within this zone the rate of damage growth is always positive. That part of a crack layer complementary to the active zone is the wake zone.

The width of the active zone was found to increase during slow crack layer propagation. Analysis of craze distribution within the active zone reveals that the craze density decreases away from the crack. Also, a considerable difference in the critical energy release rates was observed in specimens fatigued under different loading levels. This is attributed to the difference in the density of crazes at the critical crack tip.

Recently, experimental studies demonstrated that a zone in the vicinity of the crack tip, precedes the propagating crack and this zone is usually termed a plastic zone [4], process zone [5, 6], dissipation zone [7] or deformation zone [8].

The objective of this study was to examine the crack propagation in polystyrene and the influence of the active zone and the strain rate on the crack velocity, on the stress intensity factor and on the energy release rate, using the dynamic caustics method [9–11]. In addition, the energy release rate was experimentally calculated from experimental values of the stress intensity factor.

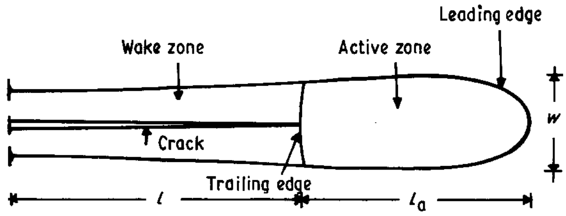

Figure 1 Schematic drawing of a crack layer.

2. The dynamic caustics method

The dynamic caustics method was used to study the variation of crack propagation velocity and stress intensity factor [9–11]. According to this method, a convergent light beam impinges on the specimen in the vicinity of the crack tip and the transmitted rays are directed on to a reference plane parallel to the plane of the specimen. These rays are scattered and concentrated along a strongly illuminated curve, or caustic, on the reference plane located at a distance z_0 from the specimen [9, 10]. From the size and angular displacement, ϕ, of the axis of symmetry of the caustic relative to the crack axis [10], it is possible to calculate the stress intensity factors K_I and K_{II} for the case of mixed-mode conditions using the relations

$$K_I = \frac{2(2\pi)^{1/2}}{3z_0 d\lambda_m^{3/2} c_t}\left[\frac{D_t^{max}}{\delta_t^{max}(v)}\right]^{5/2} \quad (1)$$

$$K_{II} = K_I \tan\left(\frac{\phi}{2}\right) \quad (2)$$

where d is the thickness of the specimen, λ_m is the magnification ratio of the optical set-up, z_0 is the distance between the specimen and the reference plane, c_t is the optical constant of the material, D_t^{max} is the maximum transverse diameter of the caustic and δ_t^{max} (v) is a correction factor which depends on the crack velocity. This correction factor is given by nomograms in Reference 9.

The elastic energy release rate, G_I, is calculated, for plane stress, by the relation

$$G_I = K_I^2/E \quad (3)$$

where E is the elastic modulus of the material.

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The values of G_I at the crack initiation is defined as G_{Ic}, the critical strain energy release rate. The fracture surface energy, γ, as defined in the Griffith theory [12] equals

$$\gamma = G_I/2 = K_I^2/2E \quad (4)$$

The stress intensity factor, K_I, is experimentally calculated from Equation 1 from the caustics. The critical stress intensity factor, K_{Ic}, or the corresponding fracture surface energy, γ, is a useful index of the ultimate properties of the material. For the critical K_{Ic}, γ_c is given by

$$\gamma_c = K_{Ic}^2/2E \quad (5)$$

3. Experimental procedure

Notched polystyrene specimens of dimensions 0.220 m × 0.050 m × 0.00025 m were used for the experimental investigation. The specimens initially contained an edge transverse notch of 25° and length $a_0 = 0.006$ m (Fig. 2).

The specimens were subjected to a dynamic tensile load to fracture using a Hydropulse high-speed testing machine with a maximum strain rate $\dot{\varepsilon} = 80\,s^{-1}$. A Cranz–Schardin high-speed camera disposing 24 sparks with a maximum frequency of 10^6 frames/s was used to record the dynamic crack propagation. In the optical set-up used in the experiments, $z_0 = 0.80$ m and $\lambda_m = 0.77$. The properties of polystyrene are $E = 2.2$ GPa, $\nu = 0.3$ and the stress optical constant $c_t = 0.74 \times 10^{-10}\,m^2 N^{-1}$. The strain rates, $\dot{\varepsilon}$, in the present experiments were 10 and 20 s^{-1}.

4. Results and discussion

In order to study the influence of the active zone of the crack tip on the crack velocity, on the stress intensity factor, K_I and on the energy release rate, G_I a number of specimens in the form shown in Fig. 2 was used. In all cases the specimens had an edge notch of 25° angle and initial length $a_0 = 0.006$ m. The dynamic loading was applied with a strain rate $\dot{\varepsilon} = 10$ and $20\,s^{-1}$.

The detailed crack propagation process may be studied from the series of photographs taken with a Cranz–Schardin high-speed camera. The series of photographs in Fig. 3 shows the crack propagation process in a polystyrene plate with a strain rate $\dot{\varepsilon} = 10\,s^{-1}$. From these photographs we may see that the form of the caustics is not influenced by the crack layer which is developed at the crack tip. This means that the magnitude of the crack layer is smaller than the initial curve magnitude of the caustics. The magnitude of the initial curve is given by [10]

$$r_0 = D_t^{max}/\lambda_m \delta_t^{max}(v) = 0.0016\ \text{m} \quad (6)$$

where D_t^{max} is the mean value of the maximum diameter of the caustic (0.0039 m), λ_m is the magnification ratio of the set-up, (0.77) and $\delta_t^{max}(v)$ is the correction factor, which depends on the velocity of the crack (3.175). Therefore, the magnitude of the crack layer must be smaller than 0.0016 m. The crack layer at the crack tip is shown in Figs 4 and 7. The crack layer, a region of crazes around the crack tip, increases as the strain rate increases. As the crack layer is developed, the crack propagation velocity decreases and thus the magnitude of the crack layer decreases. After that, a new crack acceleration is observed and a new crack layer is developed. This phenomenon is presented in Figs 4 and 7. In Fig. 4 the crack propagation velocity, v, versus the crack length, a, is presented for strain rate $\dot{\varepsilon} = 10\,s^{-1}$. The photograph at the top of figure shows the crack propagation morphology with the craze regions. In this figure we can see a correspondence of the minima of the velocity with the crack layer, while the maxima of the velocity correspond to regions of the crack path without crack layers. It is concluded from this that the crack velocity decreases with the crack layer.

The stress intensity factor, K_I is calculated using Equation 1 from the diameter of the caustics. The variation of the K_I with crack length a for strain rate $\dot{\varepsilon} = 10\,s^{-1}$ is presented in Fig. 5. From this figure it may be observed that the variation of K_I is approximately the same as the variation with the velocity.

A series of photographs in Fig. 6 shows the crack propagation process in a polystyrene plate with a strain rate $\dot{\varepsilon} = 20\,s^{-1}$. From these photographs we may see the same phenomena as in Fig. 3, but more intense.

Fig. 7 shows the variation in the crack propagation velocity, v, with the crack length, a, for strain rate $\dot{\varepsilon} = 20\,s^{-1}$. The photograph at the top of figure shows the crack propagation morphology with the craze regions. In this figure we can see that the crack layers are wider than the crack layers of the crack path in Fig. 4 and also, the crack velocities are greater than

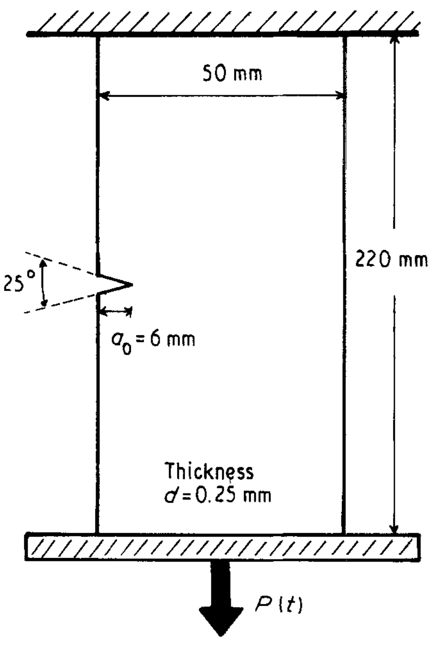

Figure 2 Geometry of a cracked plate.

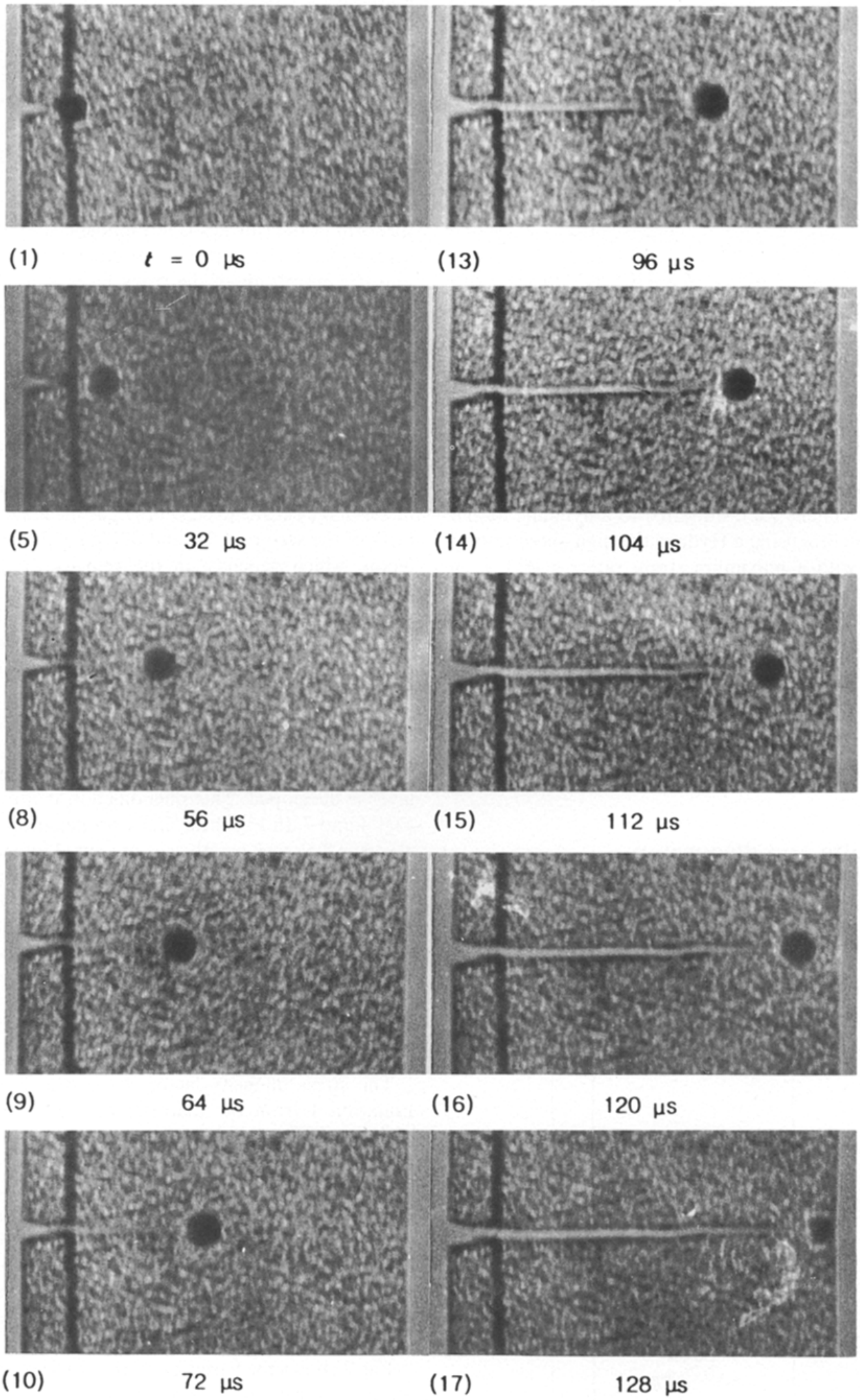

Figure 3 Series of photographs showing crack propagation in a polystyrene plate with a strain rate $\dot{\varepsilon} = 10\,s^{-1}$.

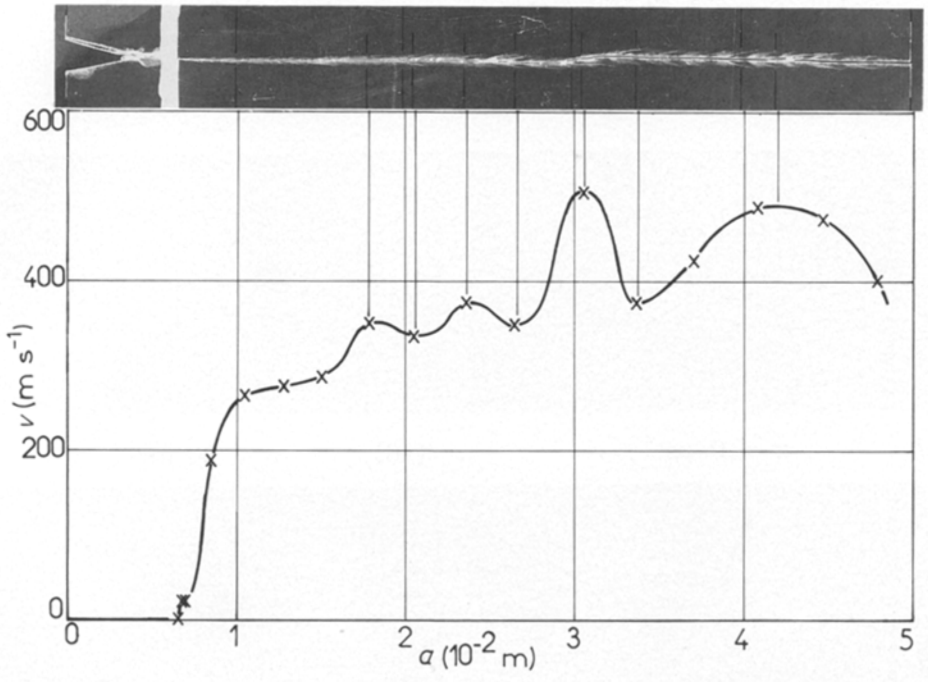

Figure 4 Variation of the crack propagation velocity, v, with crack length, a, for strain rate $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$. The photograph at the top shows the crack propagation morphology.

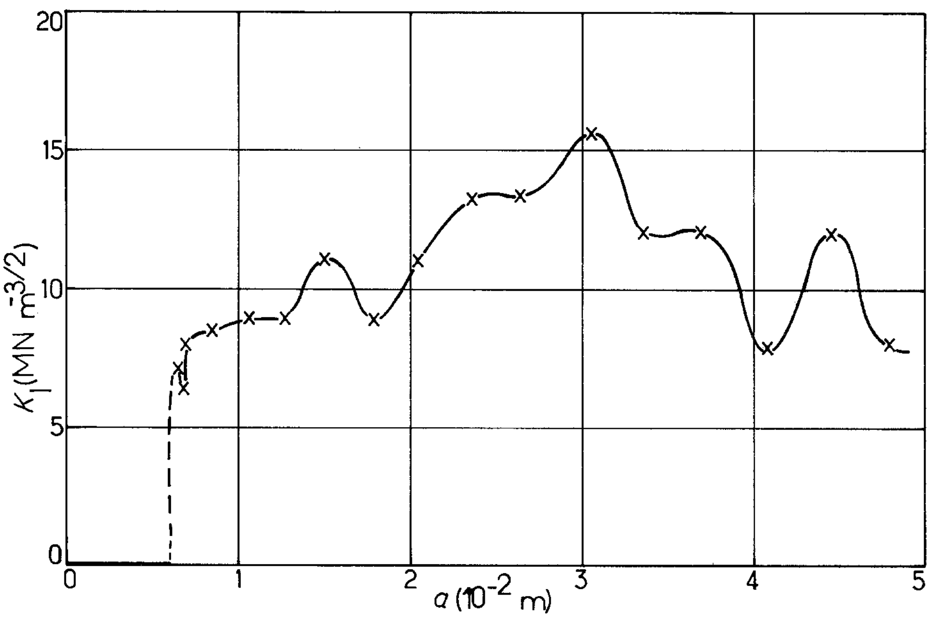

Figure 5 Variation of the stress intensity factor, K_I, with crack length, a, for strain rate $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$.

those in Fig. 4 for strain rate $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$. In addition, it may be observed in Fig. 7 that the minima of the crack velocity correspond to the crack layers, while the maxima of the velocity correspond to the path regions without crack layers (regions between crack layers).

Fig. 8 shows the variation of the stress intensity factor, K_I, with the crack length, a, for strain rate $\dot{\varepsilon} = 20\,\mathrm{s}^{-1}$.

By comparison of Figs 4 and 7 it may be observed that the crack velocity increases as the strain rate increases. The crack velocity increases smoothly upto a maximum value of 520 m s^{-1} at the position of crack path $a = 0.031$ m for $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$, while for $\dot{\varepsilon} = 20\,\mathrm{s}^{-1}$ the crack velocity rapidly increases until the maximum value of 580 m s^{-1} at the position of crack path $a = 0.029$ m. The same variation can be observed for the stress intensity factor, K_I.

Fig. 9 shows the variation of energy release rate, G_I, which was calculated using Equation 3, versus the crack length, a, for strain rate $\dot{\varepsilon} = 10$ and $20\,\mathrm{s}^{-1}$. From this figure it may be observed that the energy release rate, G_I, for strain rate $\dot{\varepsilon} = 20\,\mathrm{s}^{-1}$ is greater than the energy release rate for $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$. The critical fracture surface energy γ_c for $\dot{\varepsilon} = 10\,\mathrm{s}^{-1}$ is $\gamma_c = 11.65\,\mathrm{kJ\,m}^{-2}$ and for $\dot{\varepsilon} = 20\,\mathrm{s}^{-1}$ is $\gamma_c = 18.33\,\mathrm{kJ\,m}^{-2}$. It may also be observed that in the

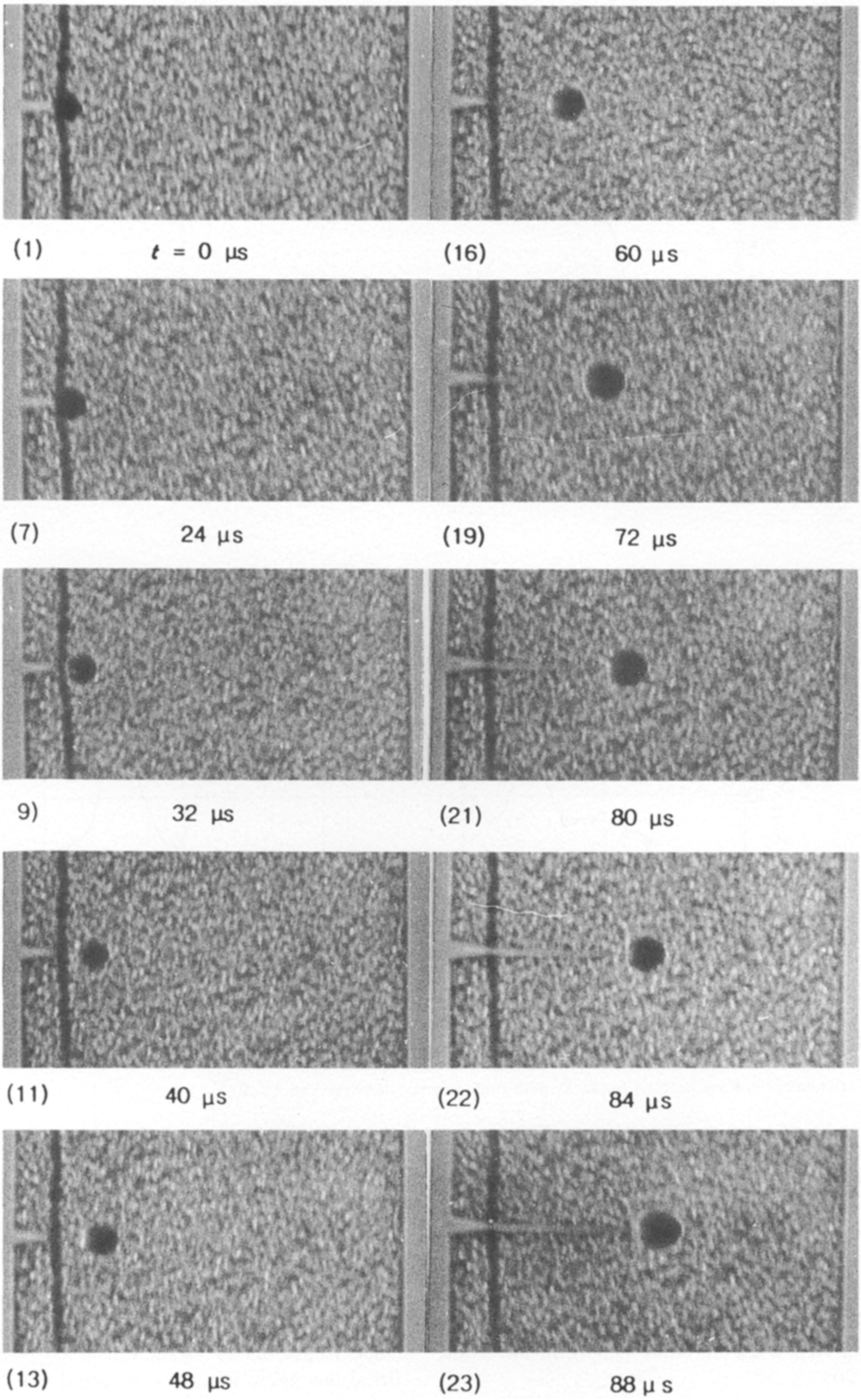

Figure 6 Series of photographs showing the crack propagation in a polystyrene plate with a strain rate $\dot{\varepsilon} = 20\,s^{-1}$.

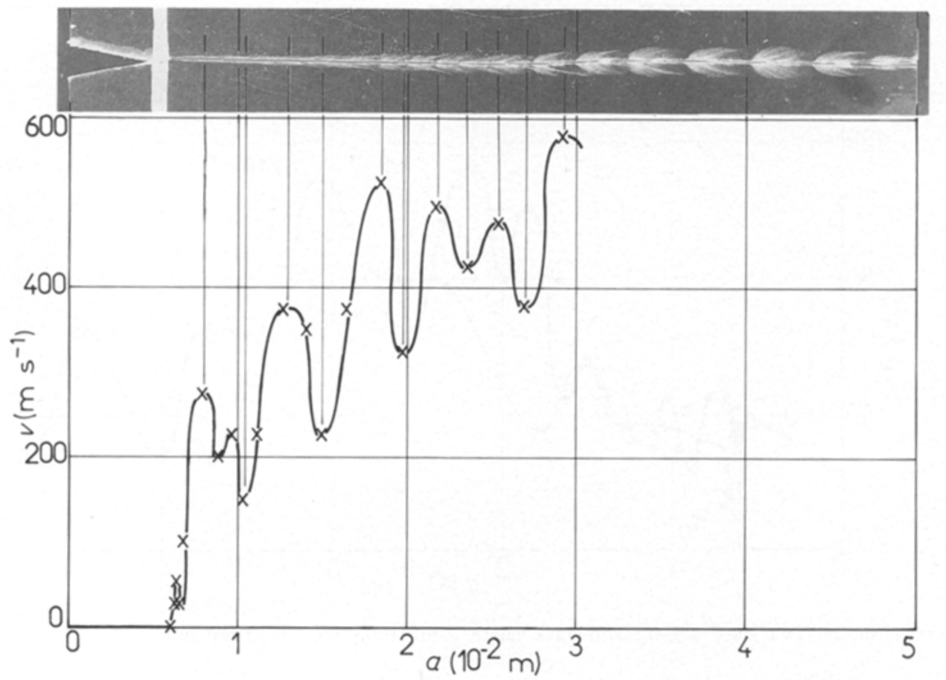

Figure 7 Variation of the crack propagation velocity, v, with the crack length, a, for strain rate $\dot{\varepsilon} = 20\,s^{-1}$. The photograph at the top shows the crack propagation morphology.

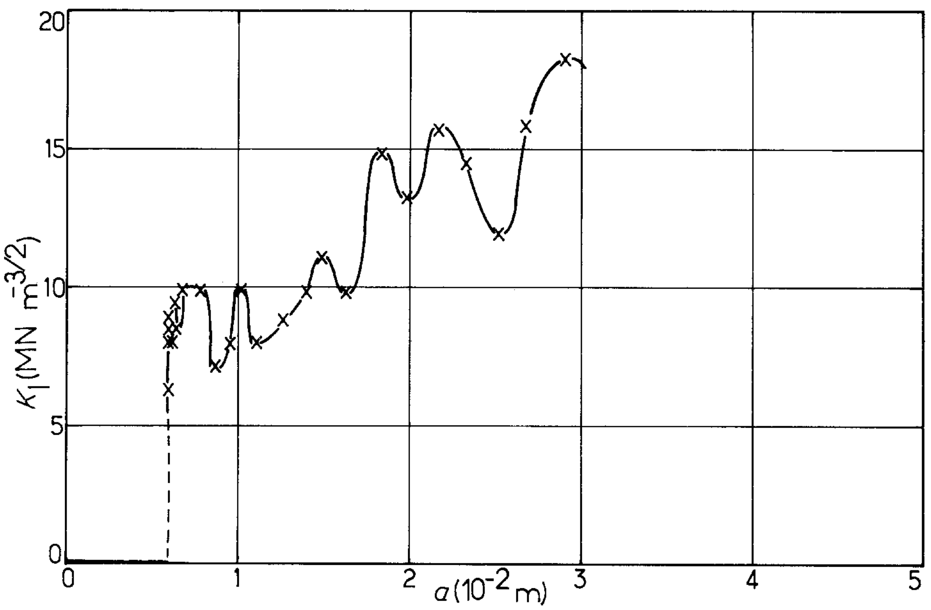

Figure 8 Variation of the stress intensity factor, K_I, with crack length, a, for strain rate $\dot{\varepsilon} = 20\,s^{-1}$.

crack layer, where there is a great craze density, the energy release rate, G_I, reduces considerably.

5. Conclusions

The effect of the crack layer on the dynamic crack propagation in polystyrene plates has been studied. The results may be summarized as follows.

1. The shape and the magnitude of the active zone (crack layer) are strongly dependent on the strain rate.
2. During crack propagation, the active zone is discontinuously developed at the crack tip.
3. The crack velocity and the stress intensity factor are reduced when active zone is developed, while they are increased in regions where active zone is not developed.
4. The active zone is the area with intense damage. Therefore, the modulus of elasticity, E, is reduced and then a decrease in the crack velocity is observed.
5. The active zone is formed ahead of the crack propagation tip but when the crack velocity is great, the active zone remains behind the crack tip until a new active zone is formed ahead of the crack tip.

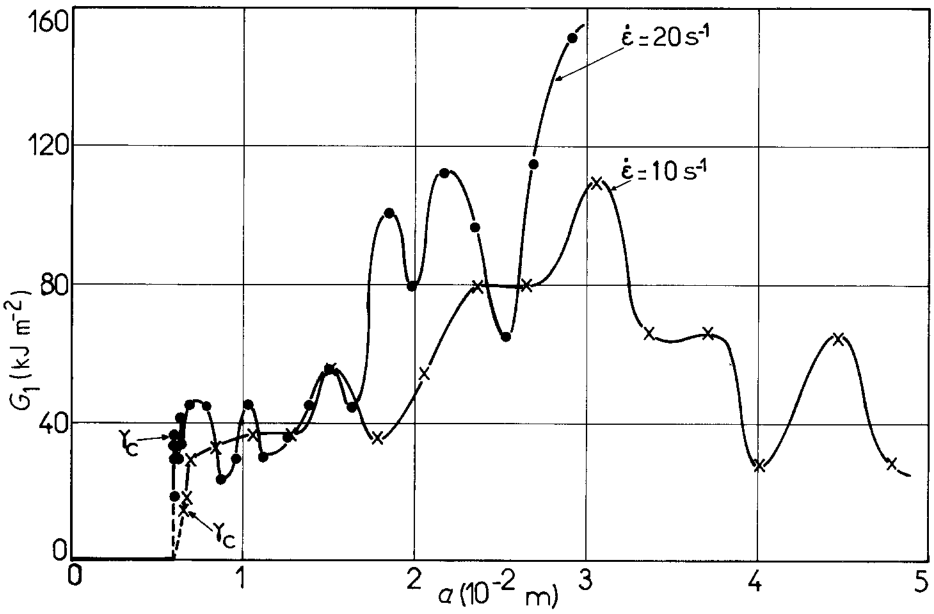

Figure 9 Variation of the energy release rate, G_I, with crack length, a, for strain rate $\dot{\varepsilon} = 10$ and $20\,s^{-1}$.

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