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MICRO-MECHANISM OF DYNAMIC CRACK PROPAGATION IN BRITTLE MATERIALS

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Résumé - Les micro-mécanismes de la propagation dynamique de fissures est étudié expérimentalement. Un essai de propagation de fissure dans des plaques de PMMA fragile est mis en oeuvre à vitesse constante en utilisant un appareil muni de mors.
La surface rompue est observée par microscopie. L'analyse de faciès paraboliques sur la surface rompue met en évidence le processus d'initiation des micro-fissures, de leur propagation et de leur coalescence jusqu'à la propagation de la fissure globale. Les conditions de l'initiation des micro-fissures aux noyaux sont obtenues par examen des faciès et par l'analyse des contraintes dynamiques.

ABSTRACT - Micro-mechanism of dynamic crack propagation is experimentally studied. A running crack experiment in brittle PMMA plates is conducted under constant velocity condition by the use of a fixed grip apparatus. The fracture surface is microscopically observed. Analysis of parabolic patterns on the fracture surface shows the process of micro-crack initiations, propagations and their coalescences to the global crack propagation. The condition of the micro-crack initiation at the nuclei is obtained from the examination of the patterns and the dynamic stress analysis.

1 - INTRODUCTION

The feature of fracture surface of a brittle material such as PMMA or glass varies depending on the propagation velocity of the crack. Generally, smooth fracture surfaces are observed in a low or middle velocity range of crack propagation, while, in very high velocity range, rough crazing surfaces are seen with sometimes bifurcations of the crack path. In microscopic aspects, the crack propagation takes place in the form of the nucleation of micro-cracks ahead of the main crack, their growth and coalescence to the main crack. Even in macroscopically smooth region, an optical or electron microscope observation reveals the existence of step lines called parabolic patterns on the fracture surface. These parabolic patterns are thought to be the trajectories of intersection between the fronts of the main crack and the micro-cracks /1/. The patterns change in shape and density with the crack velocity. The present study is focused on the mechanism of the pattern formation, and through the analysis of the mechanism, the criterion of dynamic fracture is discussed in microscopic level.

The fracture surfaces in brittle fracture have generally been discussed in terms of the crack propagation velocity as stated above. However, even if the crack velocities are in a similar range, the stress or strain state around the running crack tip may differ if the crack propagation is in acceleration or deceleration. Since the stress and/or strain state near the main crack tip can generally be a criterion of micro-crack initiation from the nuclei, the experimental study requires the condition of steady state (constant velocity) crack propagation in which the dissipation energy at the crack tip is in equilibrium with the released (elastic) energy of the system containing the crack, i. e., no change in kinetic energy. In the present work, experiment of steady state crack propagation is conducted using a crack system of a fixed sided long plate, and based on the experiment, the microscopic fracture mechanism is discussed.

2 - EXPERIMENT OF CONSTANT VELOCITY CRACK PROPAGATION

In the present study, an experiment of crack propagation in a fixed sided plate was performed for the purpose of examining the above micro-fracture mechanism. The specimen material is PMMA which is considered to be brittle in normal conditions. Schematic picture of the experimental apparatus is shown in Fig. 1. In order to assure the steady state crack propagation, slender rectangular shaped specimens [A] are used with the longer sides fixed by a set of long grips [B]. After tensile load is applied by a universal testing machine, the displacement between the grips is fixed [C]. A crack is then, triggered by a knife impact at a notch [D] put in the middle of an end side of the specimen. The resulting crack propagation path is along the longer sides direction (Mode I). The propagation velocities are obtained from the time intervals of the cuts of electrically conductive lines painted on the surface of the specimen.

An example of crack paths in the experiments is shown in Fig. 2, showing a straight stable propagation along the center line of the plate. This stability has been expected by the theoretical analysis of the running crack path by the authors /2/.

Figure 3 is the crack front velocities vs. travelling distance tested by the above apparatus. This figure shows that the crack in the present apparatus reaches its terminal velocity V_T after a short propagation from the starting point so that a constant velocity condition is obtained.

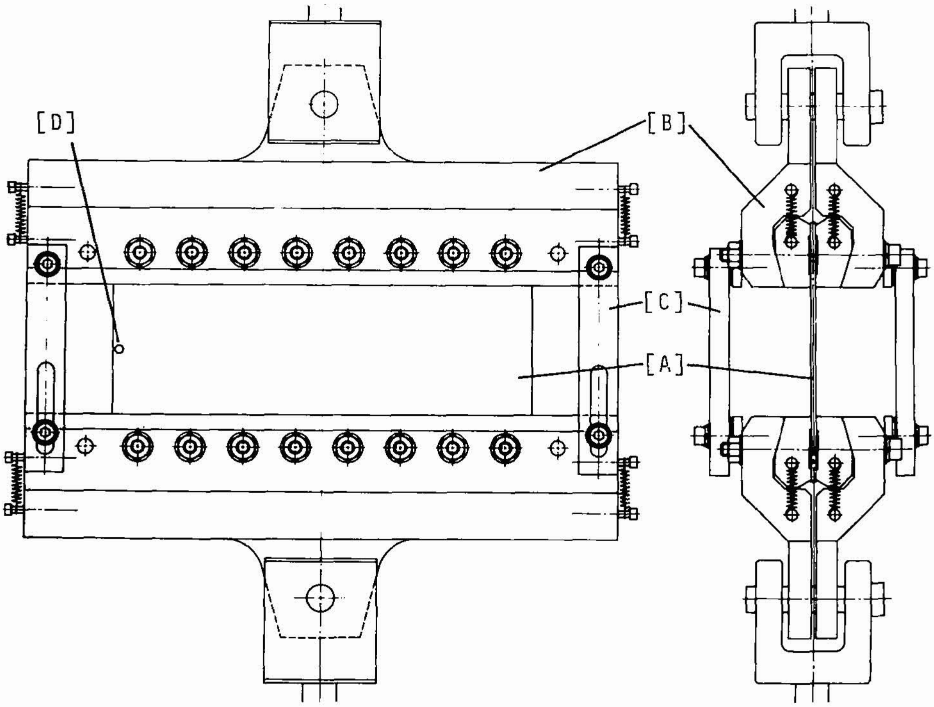


Fig. 1 - Experimental apparatus.

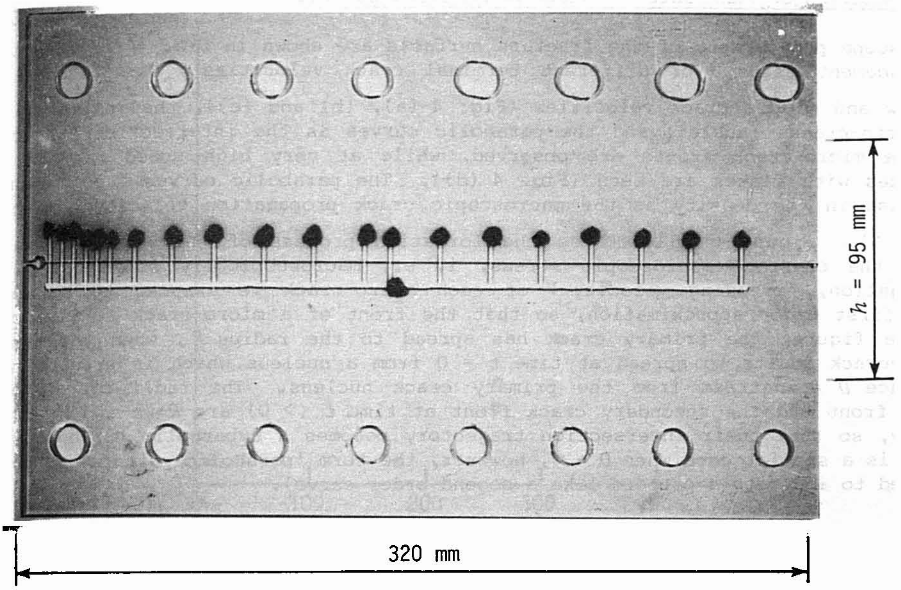


Fig. 2 - Specimen after fracture.

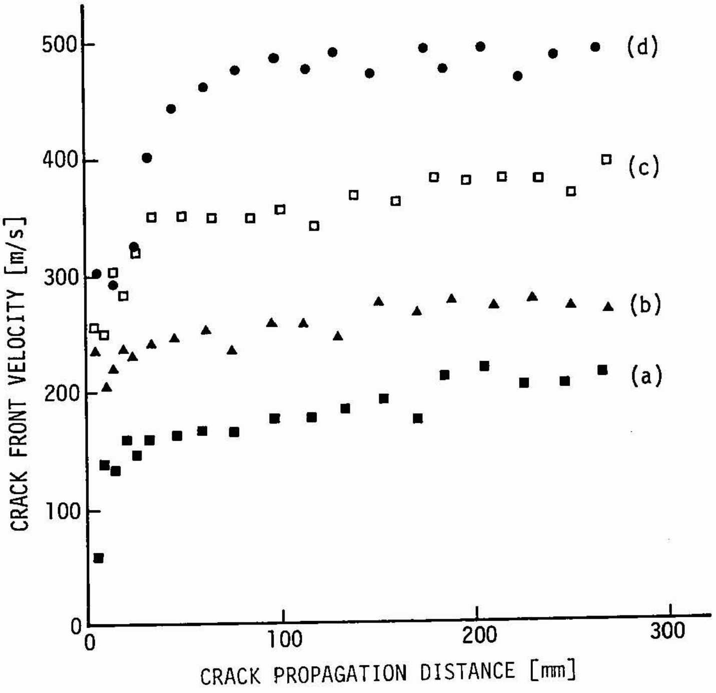


Fig. 3 - Crack front velocity vs. propagation distance.

3 - FORMATION OF PARABOLIC PATTERNS ON FRACTURE SURFACE

Microscope photographs of the fracture surfaces are shown in Fig. 4 for each tensile displacement tests (for different terminal crack velocities V_T). In the photos of low and middle crack velocities (Fig. 4-(a), (b) and (c)), the initiation sites of micro-cracks (nuclei) and the parabolic curves as the intersection trajectories of the micro-crack fronts are observed, while at very high speed region, coarse surfaces with flakes are seen (Fig. 4-(d)). The parabolic curves become blunt and increase in the density as the macroscopic crack propagation velocity V_T increases (Fig. 5). Figure 6 illustrates the formation process of the parabolic pattern. Under the constant macroscopic stress, i. e., macroscopically steady state crack propagation, spreading velocity V of each micro-crack is assumed to be constant as a first order approximation, so that the front of a micro-crack forms a circle. In the figure, the primary crack has spread to the radius R, when the secondary micro-crack starts to spread at time $t = 0$ from a nucleus which is situated at the distance D downstream from the primary crack nucleus. The radii of the primary crack front and the secondary crack front at time t (> 0) are $R+Vt$ and Vt, respectively, so that their intersection trajectory becomes a hyperbolic curve (parabolic curve is a special case when $D \to \infty$, however, the term 'parabolic pattern' is generally used to indicate a pattern like a second order curve).

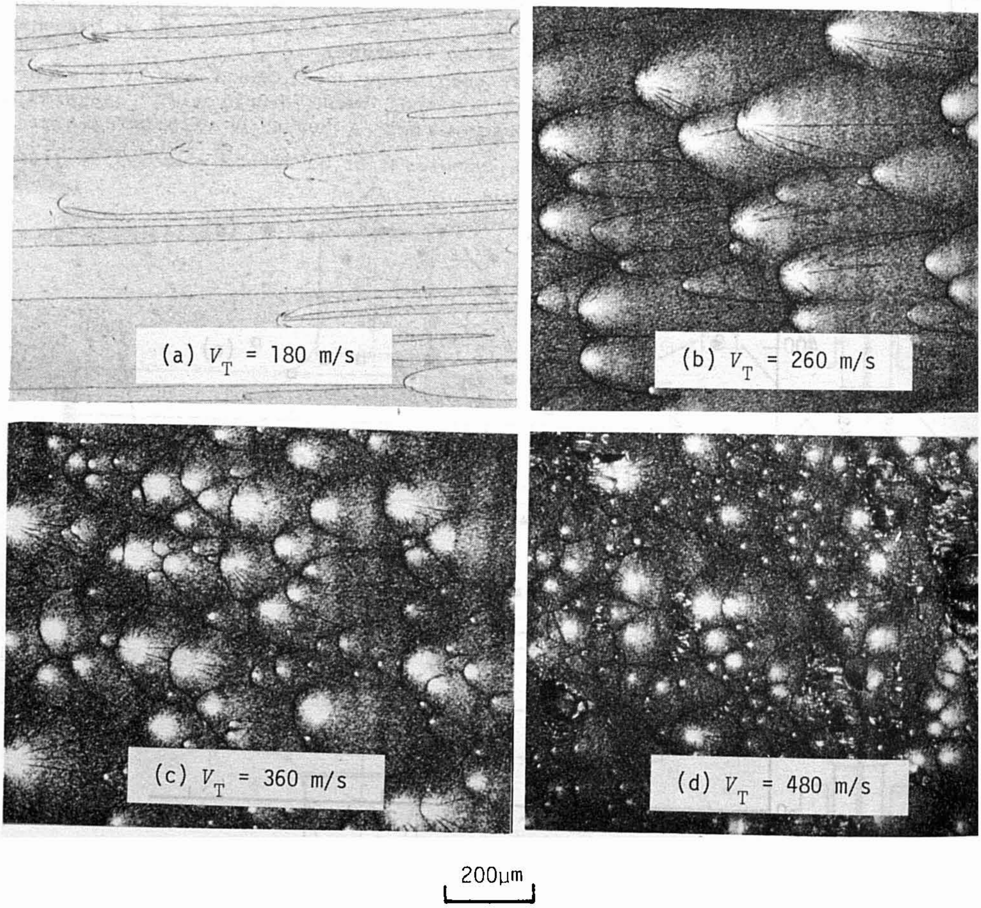


Fig. 4 - Fracture surfaces.

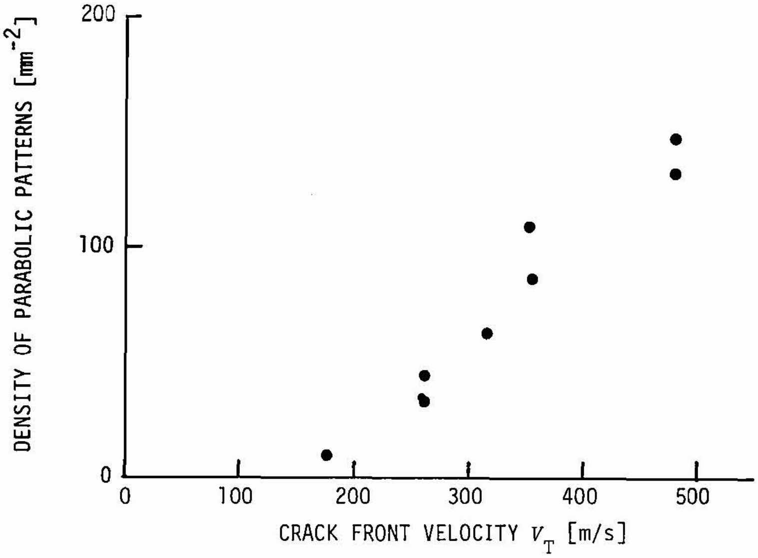
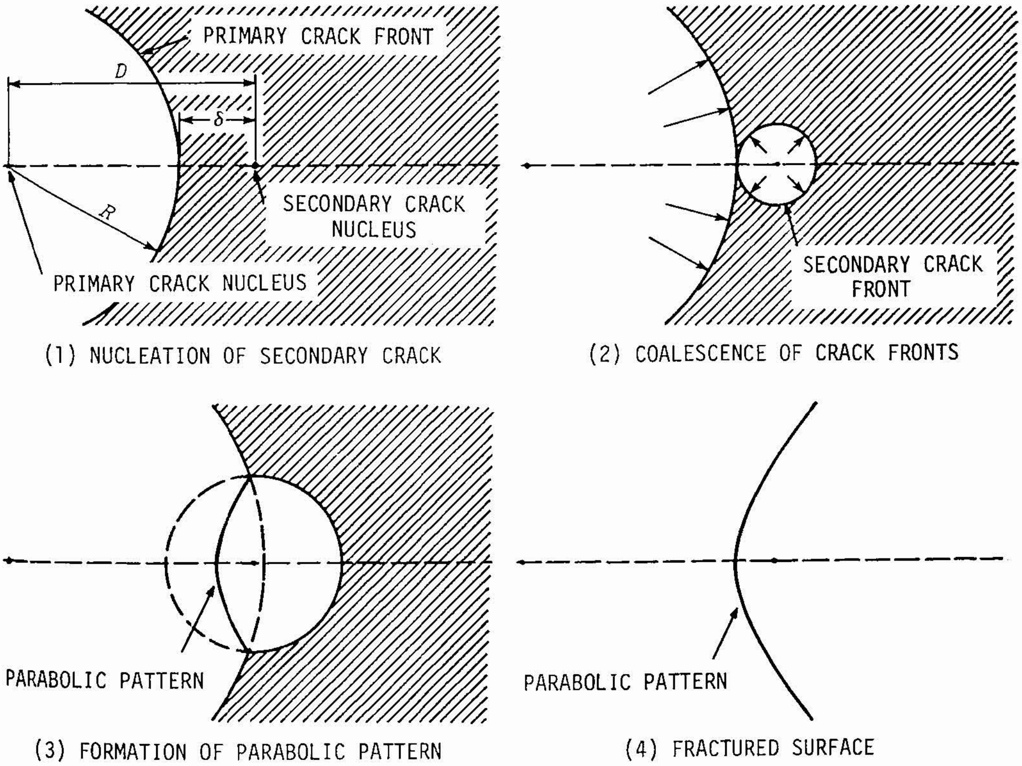


Fig. 5 - Density of parabolic patterns vs. crack front velocity.



(1) NUCLEATION OF SECONDARY CRACK

(2) COALESCENCE OF CRACK FRONTS

(3) FORMATION OF PARABOLIC PATTERN

(4) FRACTURED SURFACE

Fig. 6 - Formation process of parabolic patterns.

4 - DYNAMIC FRACTURE CRITERION IN MICROSCOPIC LEVEL

In order to examine the condition of micro-crack initiation at the nucleus, $\delta = D-R$, the distance from the primary crack front to the secondary nucleus on the crack initiation is measured for each parabolic (hyperbolic) patterns. Figure 7 shows that the average value of δ increases with the global crack velocity V_T. The stress condition at the nucleus on the initiation can be estimated by the use of the 2-dimensional elasticity theory in dynamic fracture mechanics, as δ is very small compared with the radius of primary crack front. The normal stress σ_y at a short distance x ahead of a running crack front is expressed as,

$$\sigma_y = K_{ID}/(2\pi x)^{1/2}, \tag{1}$$

where K_{ID} is the dynamic stress intensity factor. In case of a crack with a constant velocity V_T in a fixed sided plate, K_{ID} has been given by F. Nilsson /3/, as,

$$K_{ID} = [\{4s_1 s_2-(1+s_2{}^2)^2\}/\{s_1(1-s_1{}^2)\}]^{1/2}\cdot(Gv_0/h^{1/2}), \tag{2}$$

where v_0 and h are the tensile displacement between the sides and the width of the plate, respectively, and

$$s_1 = \{1-(V_T/c_1)^2\}^{1/2}, \quad s_2 = \{1-(V_T/c_2)^2\}^{1/2}, \tag{3}$$

$$c_1 = \{(\kappa+1)/(\kappa-1)\}^{1/2}\cdot(G/\rho)^{1/2}, \quad c_2 = (G/\rho)^{1/2}, \tag{4}$$

$$\kappa = 3-4\nu \text{ (Plane strain)}, \quad \kappa = (3-\nu)/(1+\nu) \text{ (Plane stress)}, \tag{5}$$

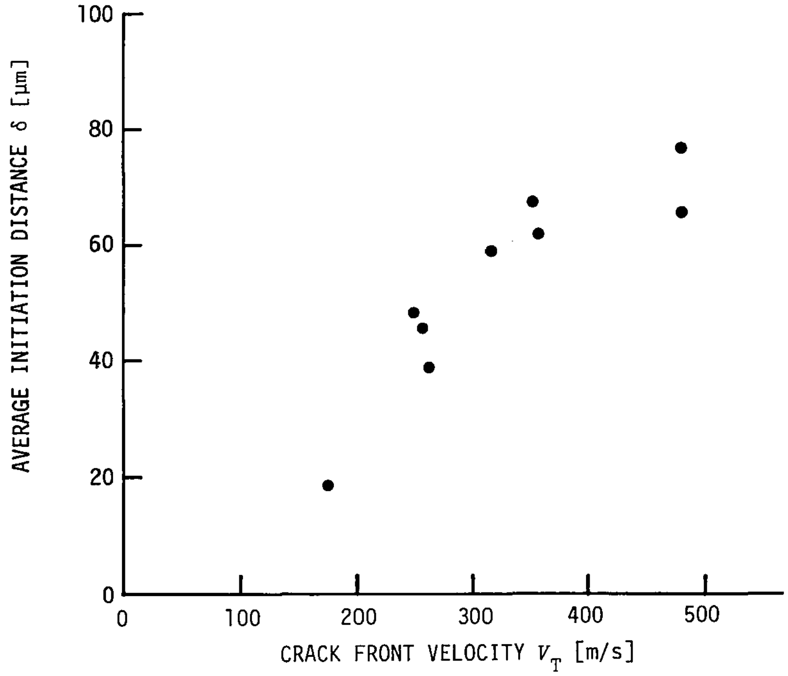


Fig. 7 - Average initiation distance from the primary crack front vs. crack front velocity.

where ρ, G and ν are the mass density, the shear modulus and the Poisson's ratio of the plate material, respectively. For the various values of V_T in the experiments, the calculated σ_y at $x = \delta$ by the above equations are plotted in Fig. 8, showing that they are almost in the same value regardless of V_T. This fact suggests that the condition of the micro-crack initiation is the stress state at the nucleus.

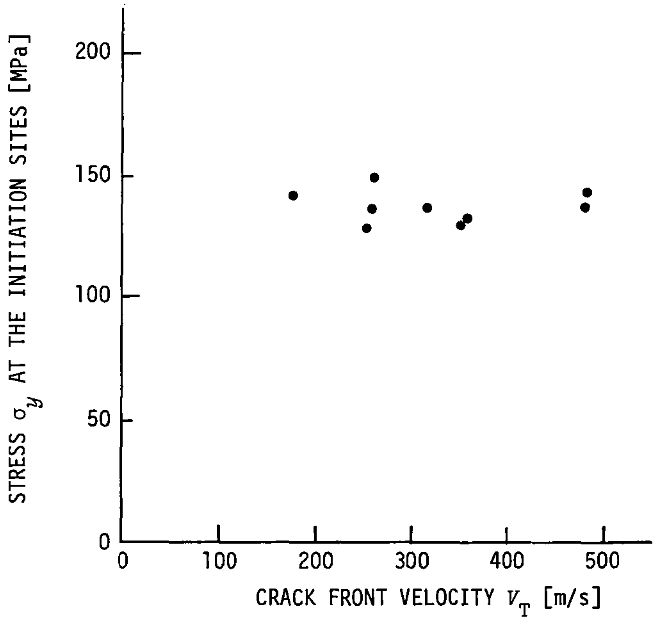


Fig. 8 - Stress at the initiation sites vs. crack front velocity.

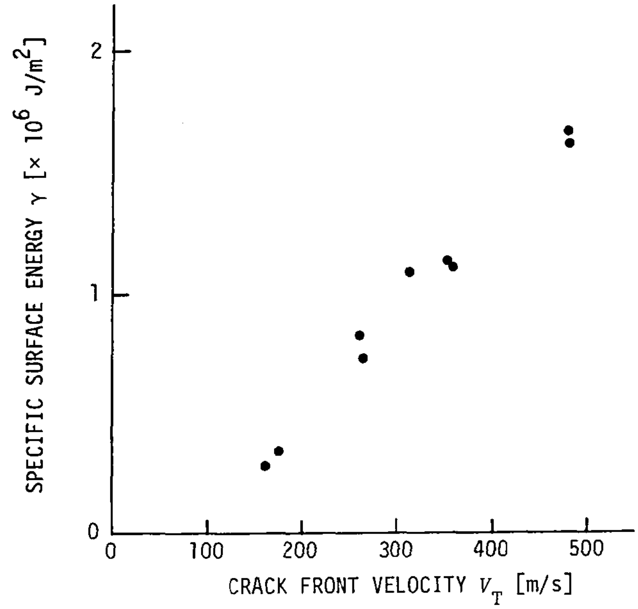


Fig. 9 - Surface energy vs. crack front velocity.

5 - DISCUSSIONS AND CONCLUSIONS

Micro-mechanism of high speed brittle crack propagation was experimentally studied. A fixed grip apparatus was devised to obtain the condition of constant velocity crack propagation. The fracture surface was microscopically examined and parabolic patterns on the surface was analyzed. Under appropriate assumptions, the initiation distance δ from the front of the primary crack was estimated. With the dynamic stress intensity factor of the running crack, the stress state at the nucleus on the initiation instant was calculated. The criterion of the micro-crack initiation was then obtained in a dynamic stress condition term.

As to the increase in the density of micro-crack nuclei with the global crack front velocity, it may be explained that in the higher velocity crack, the nuclei in the thicker layer (in the y direction) are activated to become micro-crack origins due to the increase in δ. This increase in the density and also in the depth of the parabolic step lines are considered to increase the macroscopic surface energy of the crack in addition to the rate effect of the net surface energy. The macroscopic (specific) surface energy γ in the present experiment can be obtained from the applied potential energy under the condition of constant velocity condition, as,

$$\gamma = (1/2)\cdot\{(\kappa+1)/(\kappa-1)\}\cdot(Gv_0^2/h), \qquad (6)$$

and is shown in Fig. 9 for the crack velocity V_T. The sharp rise of γ in the high region of V_T indicates the rapid increase in the density of nuclei to the transition to the coarse surface mode (Fig. 4-(d)). In the coarse surface mode, the measurement of the crack velocity shows some fluctuation, suggesting the existence of a kind of instability.

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