C-10 # Crack Velocity in Plastics

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Abstract

To measure the crack velocity and the impact force, a new type of the impact tester using cleavage technique was introduced.

The crack velocity in plastics was measured and analysed at the beginning stage of the crack propagation. And the following conclusions were obtained.

1) A group of the crack velocity values showing a distribution curve was obtained at each impact speed.
2) The maximum crack velocity in the impact test was much lower than that in the tensile test.
3) The crack velocity depended on the impact speed.
4) The ratio of the crack velocity to the longitudial wave velocity was very small.

List of key symbols

| | |
|---|---|
| $c$ | Instantaneous half-crack length, mm |
| $c_0$ | Initial half-crack length (Griffith's crack length) , mm |
| $\dot{c}$ | Crack velocity , mm/s. |
| $E$ | Young's modulus , $kg/mm^2$ |
| $F$ | External (applied) force , kg |
| $I$ | Moment of inatia of area , $mm^4$ |
| $L$ | Total crack length , mm |
| $S$ | Total surface energy , kg-mm |
| $T$ | Kinetic energy , kg-mm |
| $t$ | A half of the thickness of the specimen , mm |
| $Ub$ | Elastic strain energy by the bending , kg-mm |

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Us Elastic strain energy by the shearing, kg-mm

vl Longitudinal wave velocity, m/s.

$\gamma$ Specific surface energy, kg-mm/mm$^2$

$\delta_b$ Deflection by the bending, mm

$\delta_s$ Deflection by the shearing, mm

$\varepsilon$ Strain.

$\dot{\varepsilon}$ Strain rate, 1/s.

$\eta$ Viscosity, kg-s./mm$^2$

$\sigma$ Stress, kg/mm$^2$

$\sigma_o$ Stress required to start the crack, kg/mm$^2$

$\omega$ Width of the cross section of the specimen, mm

## 1. Introduction

Most of the plastic materials are made by means of molding. However, high precision machine elements are usually machined by turning, milling, drilling etc. to obtain dimentional accuracy.

Hence, studies on the machining of plastics are being extended with the increasing demand of plastics as engineering materials.

In the case of the cutting of plastics(1), under certain cutting conditions, the chip fromation changes from "flow type" to "crack type" and, at the same time, the cutting force decreases (Fig. 1) with the increase of the cutting speed (the deforming speed, in other words).

The high speed cutting saves time and power of machining. However, it gives the rough machined surface and increases the residual cracks on the surface which lead to the fracture in the finished products.

According to our experimental data, when the cutting speed was increased up to 30 m/s. and over, an appreciable decrease of cutting force and the diminution in the chip size were observed (Fig. 1).

If it is possible to make the cutting speed faster than the crack velocity it may be possible to shear the chip before cracks are propagated. From this stand point, it becomes necessary to measure the crack velocity during cutting. The direct measurement of the crack velocity during cutting is very difficult.

In this report, the fracture phenomena in plastics accompanied by brittle crack propagation produced at the edge point of a cutting tool were observed and discussed. And a new method for measuring the crack velocity was proposed.





## 2. Experimental method

Fig. 2 shows a picture of the crack velocity measuring apparatus used in the experiment, in which a high speed steel wedge was used in place of a cutting tool. The apparatus was so operated that it gave the similar crack to obtain by the actual cutting machine.

A wedge (knife edge) was fixed to the pendulum tip similar to that of the Charpy's impact tester and this wedge was knocked against the specimen plastics plate. The impact speed was varied between 0.4 m/s. and 2.4m/s. by adjusting the swing angle of the pendulum. The impact force was measured by the impact dynamometer using $BaTiO_3$ piezo elements equipped in the back side of the specimen holder.

When the wedge strikes against the end face of the specimen, a crack appears instantly at the impact point and propagates in the direction of the impact. Two graphite bands are glued in parallel to the specimen surface and the bands are electrified prior to the impact test. When the crack propagates, the conductor bands are broken one by one. By measuring the distance between the two graphite bands and the time interval between the two "circut-breaks", the mean propagation velocity can be estimated. This method was used by Hudson-Greenfield(2), Dimmick(3) in their studies on the crack velocity in metal or glass. They used platinum or chromium wire as the conductor band. The fracture strength of the conductor band must be small enough not to disturb the natural crack propagation in the specimen. Hence, the authors used the glued grapfite powder bands instead of metal wire as the conductor in the measurement of the crack velocity in plastics. The photograph of the specimens are shown in Fig. 3. The dimension of the specimen is (25x20x3)mm, the crack propagated parallel with the side faces.

The block diagram of the measuring apparatus is shown in Fig. 4. The power source and the glued graphite band forms an electric circuit. When the first band is cut-off by the crack propagation the electric resistance of the circuit becomes infinite, which causes a sudden step-up in terminal voltage. By the second band cut-off, another step-up of terminal voltage occures in a similar manner. The terminal voltage changes are observed by a dual-beam synchroscope.

The horizontal sweep of the synchroscope is started just before the impact by the impulse from a phototransister. The phototransister is actioned by the reflected light coming from the mirror attached to the pendulum. Only when the mirror is in a certain position, it can supply the light to the phototransister pick-up. By this apparutus, the starting time of the horizontal sweep can be synchronized with a certain instant of the pendulum action (just before the impact).

Fig. 5 shows a typical record as drawn on the screen of the synchroscope. The time interval between the two voltage step-up curve indicates the time required for the crack propagation between the two glued graphite bands. The percentage error of the time interval measurement in about ± 2%. The horizontal sweep time is previously calibrated. The distance between the two graphite bands glued to the top surface of the specimen is approximately 12 mm. However, the crack propagation distance between the two bands is measured along the crack. The distance between the first band and the end face where the crack starts is 4 mm. The percentage error of the crack distance measurement is about ± 2.5%.

And, the sound velocity (longitudinal wave velocity) as shown in Fig.6 was measured by pulse method. Fig. 7 shows a block diagram of the sound velocity measuring apparatus.

## 3. Results and Discussion

The distribution of the crack velocity in Polymethly metacrylate (Poly(MMA)) and Unsaturated Polyester obtained by 30 to 80 tests under the same conditions were shown in Fig. 8,9,10.

### 1) The distribution of crack velocity

The previous investigations dealt mainly with the calculation and measurement of the maximum crack velocity, and none have reported on the distribution of the crack velocity. According to our experimental results, the crack velocity has some distribution as shown in Fig. 8,9,10. The distribution curve of the crack velocity at the beginning stage of the crack propagation is very similar to that obtained in the fracture strength measurement(4). Such a distribution may be presumbly the uneven quality of the plastics plate as a specimen, and by the time difference in the initiation of the crack nucleus according to the impact conditions.

### 2) The crack velocity in the impact test

The propagation velocity of the crack produced by striking specimen with a wedge is considerably low as compared to those obtained by other workers in their tensile test. The crack velocity in the tesile test by Schardin (5) using Poly(MMA) is $\dot{C}$=400–700 m/s., which is 20 times higher than that obtained by the authors. And, the crack velocity at the beginning stage obtained by Dulaey and Brace (6) in their tensile test is 200 m/s., which is ten times higher than the authors' data.

In the case of the impact test by a wedge, since the load is applied to the end face of the specimen, the distribution of stress can not be so uniform as in the case of the tensile test. It is difficult to analyse the stress distribution in this case. However, the energy which induces the propagation of the crack may be calculated as follows according to the cleavage methord proposed by Gilman (7) and Berry (8).

Since the specimen used in the test is a short rectangle, the deflection caused by shear stress cannot be neglected. Thus, taking the deflection by shear stress into consideration, the equilibrium equation of the cleavage fracture is given as follows (Fig. 11).

$$S + T + U_b + U_s - F(\delta_b + \delta_s) = 0$$

$$S = \gamma \omega L$$

$$T = 12(L/t)^2(\dot{c}/v_l)^2\, U_b$$

$$U_b = F^2L^3/6EI$$

$$U_s = (t/L)^2\, U_b$$





$$F\delta_b = 2U_b$$

$$F\delta_s = 2(t/L)^2\, U_b$$

From the above equation, the crack velocity $\dot{c}$ is shown as following,

$$\dot{c} = \frac{1}{2\sqrt{3}}\, v_l\, \frac{t}{L}\sqrt{1 + \left(\frac{t}{L}\right)^2 - \frac{S}{U_b}}$$

The second term in the root $((t/L)^2)$ shows the shearing effect, which causes a small increase in the crack velocity. As shown in the formula, the crack velocity in the impact test is usually low as compared to that in the tensile test owing to the shape effect (t/L).

Results obtained by authors using the cleavage technique are summarized in Table 1, together with the comparative values for the tension method.

### 3) The dependency of the crack velocity on the impact speed

Fig. 10 shows that the distribution curve of the crack velocity shifts towards a higher value of the crack velocity with the increase of the impact speed. As shown in Fig. 12, the mean crack velocity and the maximum crack velocity increase with the increase of the impact speed.

On the other hand, by measuring the change in the impact force during the test the crack energy, the maximum impact force and the contact time between the edge and the specimen can be calculated.

Fig. 13 shows that the cleavage force Ft increases with the increase of the impact speed. On the other hand, the cleavage force may also depend on the depth of penetration until the cracking begins. Thus, it becomes necessary to investigate the depth of penetration at the starting time of crack propagation. Fig. 14 shows the contact time $t_c$(the interval between the impact and the crack starting) and the calculated depth of the penetration ($v_0$ x $t_c$) is varied with the impact speed, assuming that the impact speed is constant during the contact time. It is clearly observed from Fig. 14 that the depth of penetration is almost not influenced by the impact speed. Thus, it can be considered that the change in the cleavage force by the impact speed depends on the time effect on the eleavage stress.

If the stress in the specimen is assumed to vary in accordance with the retardation phenomenon of the strain, the time effect of the cleavage stress may be appropriately explained by a rheological model as presented by Voigt. Thus, the time effect is simply expressed as follows,

$$\sigma = E\varepsilon + \eta\dot{\varepsilon}$$

As shown in the above equation, the cleavage force increases with the increase of the impact speed (deforming speed).

On the other hand, from the Griffith-Mott's equation (10), the crack velocity is represented as follows,

$$\dot{c} = \sqrt{\frac{2\pi}{\kappa}}\, v_l \left(1 - \frac{c_0}{c}\right)^{\frac{1}{2}}$$

where $\kappa$ = constant

$c_0$ = Griffith's crack length = $\dfrac{2\gamma E}{\pi \sigma^2}$

Therefore, the crack velocity

$$\dot{c} = \sqrt{\frac{2\pi}{\kappa}}\, v_l \left(1 - \frac{\sigma_0}{\sigma}\right)^{\frac{1}{2}}$$

Thus, the crack velocity increases with the increase of the cleavage stress and approaches to a constant value.

Fig. 15 shows the relation between the cleavage force $F_t$ and the crack velocity.

Thus, based on the above observation, it may be concluded that the crack velocity increase with increasing the impact speed is brought about by the increase of the cleavage force or the stress in the vicinity of the crack tip caused by the time effect on the impact speed.


Reference

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Table 1.

Crack velocities of plastics

| Method | Plastics | $\dot{c}$ m/s. | $v_1$ m/s. | $\dot{c}/v_1$ | Referance |
|---|---|---|---|---|---|
| Cleavage (impact) | Poly(MMA) | 9-50 | 2600[1] | 0.003-0.02 | Authors |
| | Unsaturated Polyester | 40-270 | 2200[1] | 0.02-0.13 | |
| Tension (dynamic) | Poly(MMA) | 400-700 | 1870[2] | 0.21-0.37 | Schardin (5) |
| Tension (static) | Poly(MMA) | 170-210 | 1870 | 0.09-0.11 | |
| Tension | Poly(MMA) | 220 (in beginning) 650 (in terminal) | 1870[2] 1870 | 0.11 0.35 | Dulaney, Brace (6) |
| Tension | Poly(MMA) | 100 | 400 | 0.25 | Bueche, White (9) |
| | Irradiated Polyethylene | 40-100 | 100 | 0.4-0.8 | |

Frequency, 1 : 1 Mc, 2 : 1 Kc.

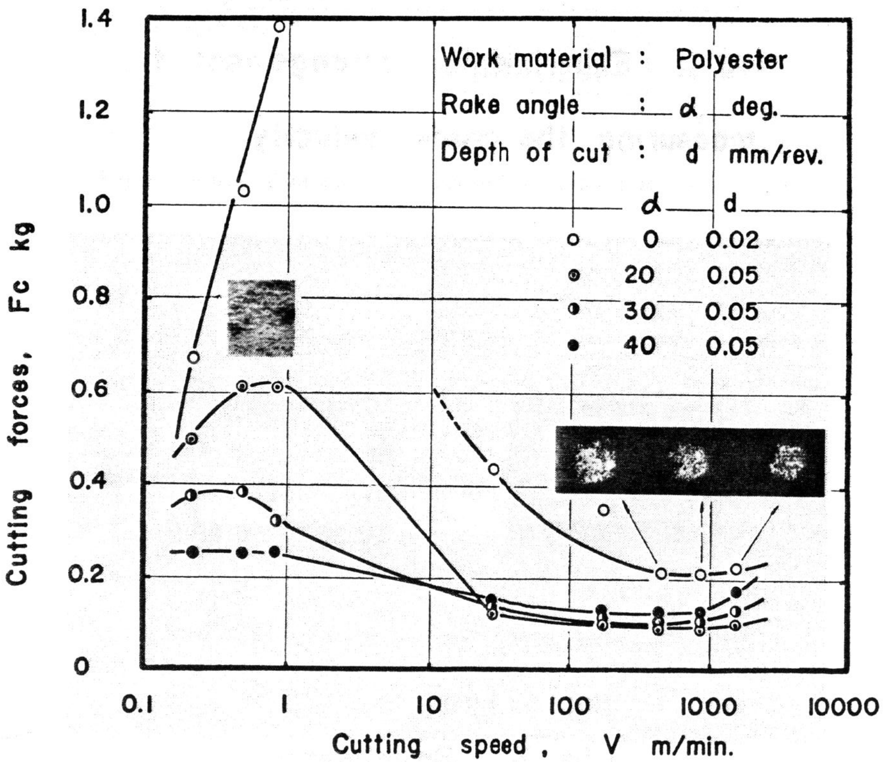


Fig. 1, Effect of cutting speed on cutting force in plastics cutting.

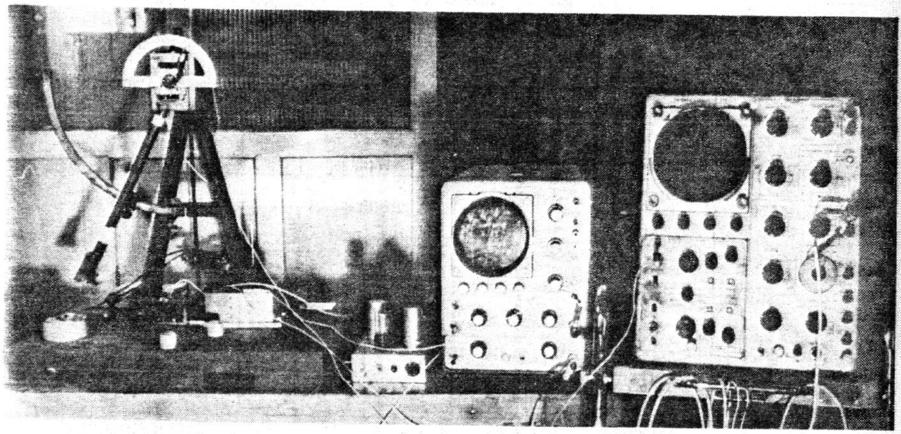

Fig. 2. Experimental arrangement for measuring the crack velocity.

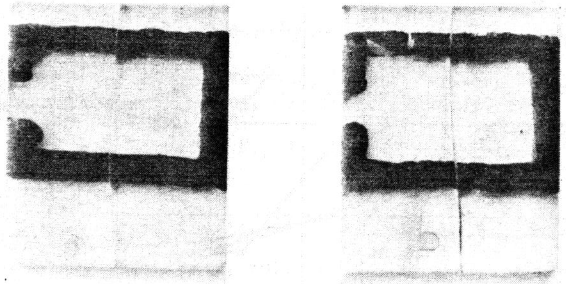

Fig. 3. Specimens.





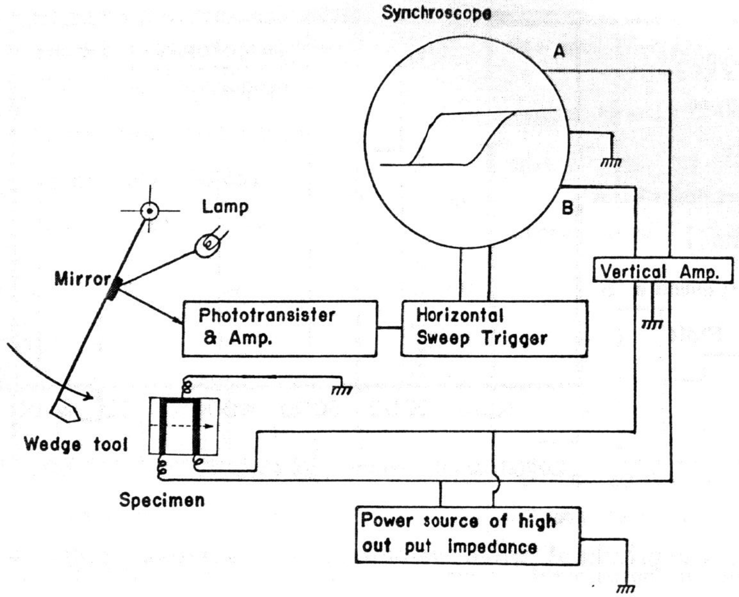


Fig. 4, Block diagram of a measuring apparatus.

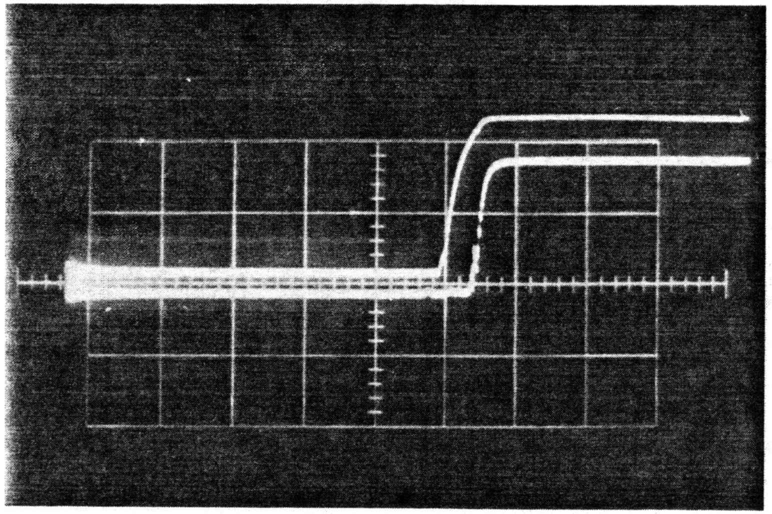

Fig. 5. A typical record obtained from propagation of a crack.

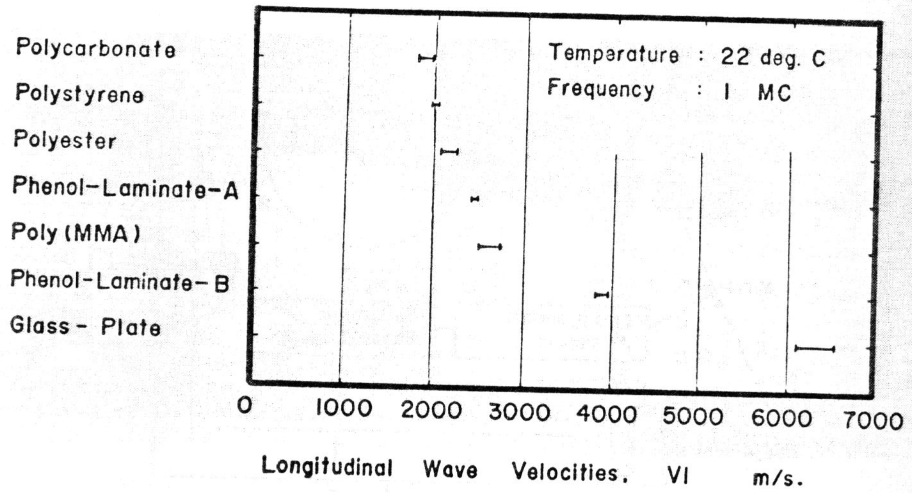


Fig. 6. Longitudinal wave velocities of various plastics.

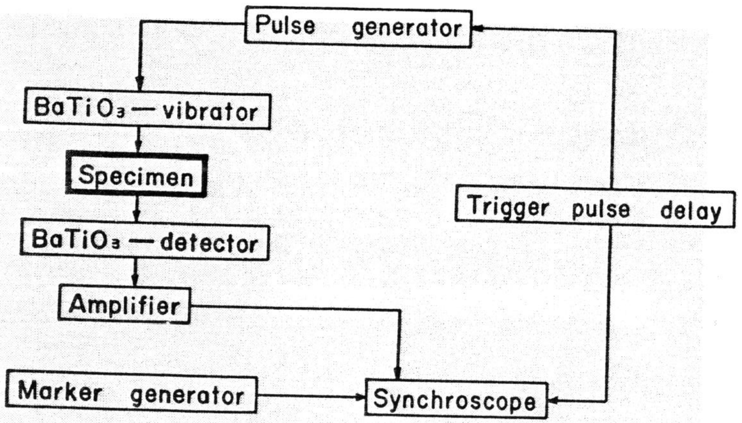


Fig. 7. Block diagram of appartus for measuring longitudinal wave velocity.





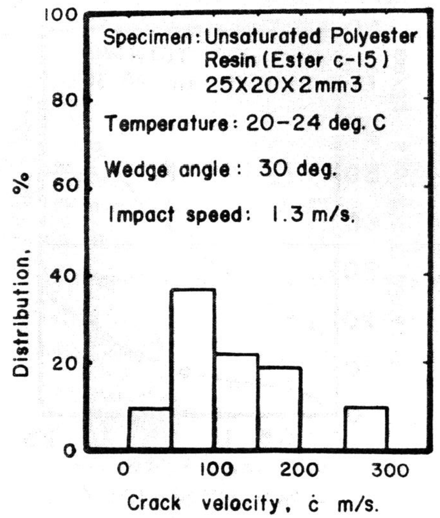


Fig. 8. Distribution of the crack velocity for Unsaturated Polyester.

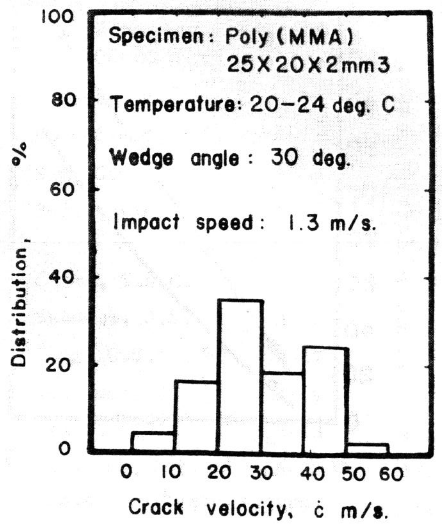


Fig. 9. Distribution of the crack velocity for Poly (MMA).

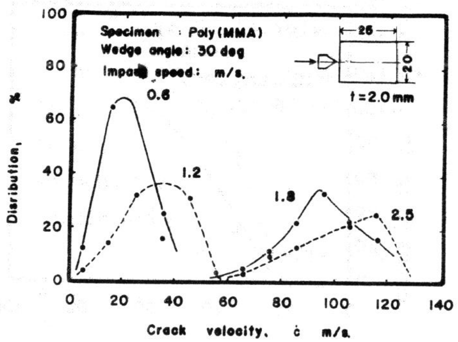


Fig. 10. Velocity distribution at the various impact speed.

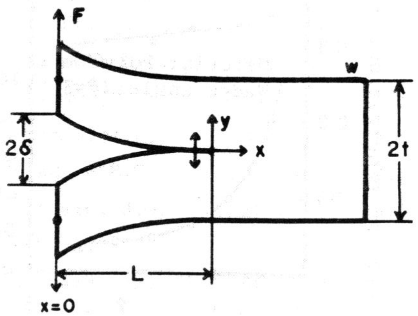


Fig. 11, Schematic diagram of cleavage technique.

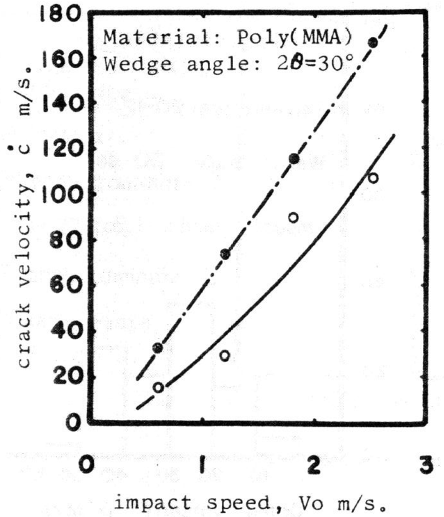


Fig. 12, Relation between impact speed and crack velocity.

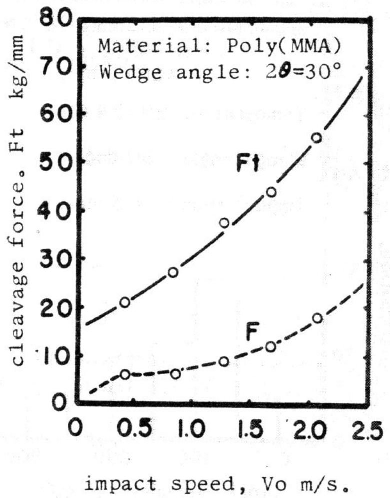


Fig. 13, Relation between impact speed and cleavage force.

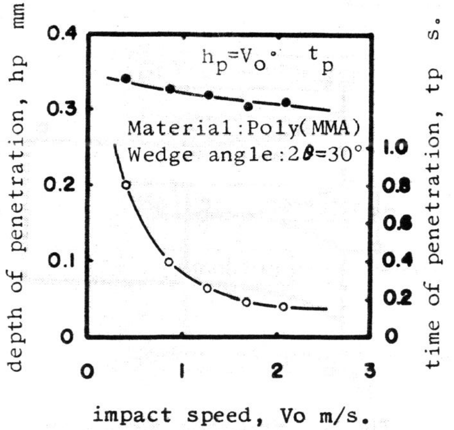


Fig. 14, Relation between impact speed and depth of penetration.

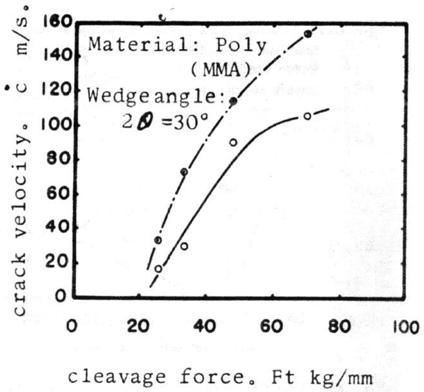


Fig. 15, Relation between crack velocity and cleavage force.