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LETTER

Mode-I fracture toughness of PMMA at high loading rates

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Polymethyl methacrylate (PMMA) has been employed widely as a structural material due to its excellent properties. Such material is subjected to dynamic loading in engineering applications such as aircraft and automotive components. Hence it is important to investigate the dynamic fracture behavior of PMMA under high-loading-rate conditions. Many experimental techniques have been proposed to test dynamic fracture behavior of materials. One of the effective experimental techniques that has been used often is the split Hopkinson pressure bar (SHPB). A number of specimen geometries such as three-point bend specimen and wedge-shaped specimen as well as compact compression specimen have been used in the conventional SHPB apparatus [1–5]. Brazilian disk specimen (also called central cracked circular disk) has been used widely to measure the fracture properties of brittle materials [6–9], because this disk configuration can cover the entire mode mixity range from pure mode-I to pure mode-II by changing the loading angle (the angle of inclination of the crack relative to the line of loading).

An experimental method for measuring dynamic fracture toughness of brittle materials using Brazilian disk specimen in SHPB system was proposed in the present paper. The pure mode-I fracture behavior of PMMA under high loading-rate conditions was investigated.

The Brazilian disk specimen and the loading configuration are depicted in Fig. 1. The diameter of the disk and the crack length are denoted as D and $2a$, respectively. A pair of compressive load, P, is applied at the boundary and across the diameter of the disk. Dong et al. [10] gave explicit expressions of stress intensity factors at the crack tip in the central cracked circular disk for isotropic brittle materials. For pure mode-I loading condition, the loading angle should be $\theta = 0$, which means that the load line is through the crack plane. The stress intensity factor for pure mode-I crack is expressed in Eq. (1).

$$K_I = \frac{2P}{\pi BD}\sqrt{\pi a}F_I(\alpha) \tag{1}$$

where P is the applied compressive load, B is the disk thickness and α is the ratio of crack length to disk diameter ($2a/D$). $F_{\mathrm{I}}(\alpha)$ is the stress intensity geometry function. In the case of dynamic loading, the dynamic stress intensity factor for pure mode-I crack is approximately estimated extending the expression in Eq. (1)

$$K_{\mathrm{I}}^d(t) = \frac{2P(t)}{\pi BD}\sqrt{\pi a}F_I(\alpha) \tag{2}$$

where $P(t)$ is the impact load and t represents time. The critical dynamic stress intensity factor (CDSIF) K_{Ic}^d of the brittle material under high loading-rate conditions can be determined from the critical impact load, Pcr, at the moment of crack initiation. The average loading rate is quantified by the parameter, stress intensity rate $\dot{K}_I$, which is defined as

$$\dot{K}_I = \frac{K_{Ic}^d}{\Delta t} \tag{3}$$

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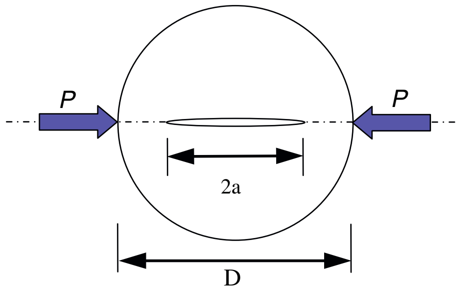

Fig. 1 Schematic diagram of the Brazilian disk specimen for measuring pure mode-I fracture toughness

where Δt is the time needed for the impact load to reach its critical value at the crack initiation.

To achieve dynamic loading conditions, the Brazilian disk specimen is sandwiched between the input bar and the output bar in the SHPB testing system. The schematic illustration of the testing configuration is shown in Fig. 2. The compressive incident stress pulse travels along the input bar to the input bar/specimen interface, part of which is reflected back to the input bar, while part of which is transmitted through the disk specimen to the output bar. The time histories of the signals from strain gages G1 and G2 mounted on both the input and output bars are recorded using a digital oscilloscope. According to the one-dimensional theory of elastic wave propagation, the impact force in the disk specimen can be obtained from the following relation

$$P(t) = \frac{1}{2}[P_L(t) + P_R(t)] = \frac{1}{2}EA[\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \qquad (4)$$

where $P_L(t)$ and $P_R(t)$ are the impact forces at the left and right interfaces between the disk specimen and the input/output bars, respectively. E and A are the Young's modulus and the cross-sectional area of the bar, respectively. $\varepsilon_i(t)$ and $\varepsilon_r(t)$ are the incident and reflected strain histories measured in the input bar and $\varepsilon_t(t)$ is the strain history measured in the output bar. The peak value of the impact force corresponding to the crack initiation is used as the critical impact load to calculate the CDSIF value of the Brazilian disk material [11].

The material tested in this investigation was a commercial PMMA whose density is 1180 kg/m^3. Brazilian disk specimens were all manufactured from the same plate. A diamond saw with a thickness of 0.19 mm was used to make the chevron notch in the center of the disk, as shown in Fig. 3. A hand saw then was used to cut out the chevrons and sharpen the tips of the notch. The nominal thickness and diameter of the specimen were $B = 5.0$ mm and $D = 19.17$ mm, respectively. The nominal length of the shape notch was $2a = 11.50$ mm corresponding to the nominal relative notch length $\alpha = 0.6$. The values of B, D and a were measured independently before each experiment. Dynamic fracture testing was conducted on 14.5 mm diameter steel bars. Due to the low-strength property of the PMMA material, the semi-conductive strain gage was used on the output bar to increase the amplitude of the transmitted signal. In the current investigation, our only concern is the dynamic fracture properties of the PMMA under pure mode-I loading conditions. Therefore, the loading angle $\theta = 0^\circ$ was chosen, which means that the axis of the input/output bar is through the notch plane. A total of nine specimens were tested under dynamic loading and all experiments were carried out at room temperature. Furthermore, the quasi-static Brazilian disk test for the PMMA was carried out using a conventional Shimadzu-5000 testing machine at a constant displacement rate of 0.08 mm/min [12].

Records from a typical dynamic fracture experiment conducted in the SHPB for a Brazilian disk specimen are shown in Fig. 4. The solid line is the signal recorded from the strain gage G1 on the input bar and the dashed line is the signal obtained from the strain gage G2 on the output bar. It should be noted that the transmitted pulse reaches its peak value before completion of the entire incident pulse. Furthermore, the transmitted pulse drops quickly at the peak value.

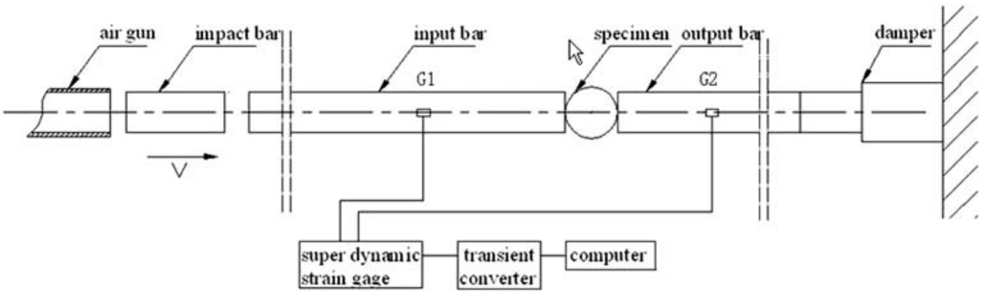

Fig. 2 Schematic illustration of the Brazilian specimen-SHPB testing system

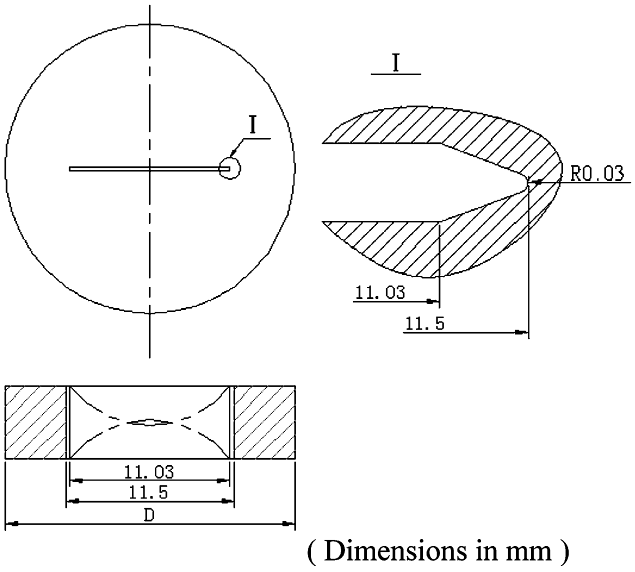

Fig. 3 Schematic illustration of sharp-notched Brazilian disk specimen geometry

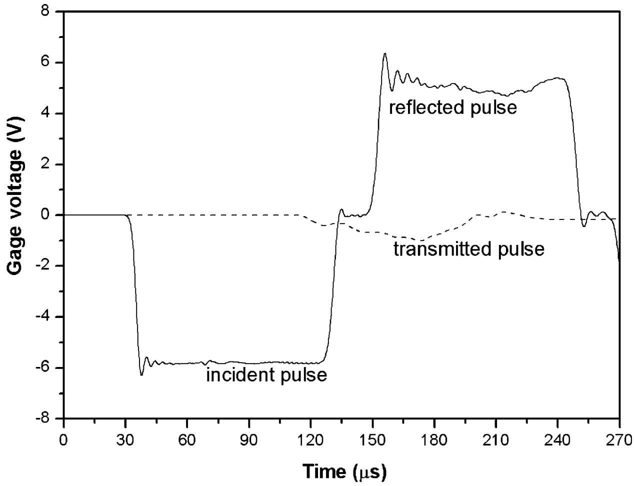

Fig. 4 Strain gage signals recorded from the input/output bars

These gage signals were processed to determine the impact force in the specimen and the maximum impact force was applied to obtain the dynamic fracture toughness. The quasi-static and dynamic results are plotted in Fig. 5. As can be seen, the measured values of K_{Ic}^{d} under dynamic loading conditions are much higher than the quasi-static one and increase significantly with increasing stress intensity rate within the investigated rate range of 7.19×10^4 MPam$^{1/2}$ s^{-1}–1.90×10^5 MPam$^{1/2}$ s^{-1}. Figure 5 also presents the results for PMMA obtained by Rittel et al. [5] who used the compact compression specimen in the SHPB. Although our results in the present work are higher than theirs, a common trend that the value of K_{Ic}^{d} increases with loading rate can be observed. Scanning electron microscope observation on the fracture surface in the vicinity of the notch front of a dynamically loaded specimen was conducted and the typical fractograph is shown in Fig. 6. It can be clearly seen that the fracture surface of the PMMA under pure mode-I dynamic loading is characterized by the conic marking together with a dark radiative zone inside. This observed feature of conic markings can also be found on the fracture surface of the quasi-statically loaded specimen [12]. The direction of the apexes of the markings is opposite to the crack-propagation direction. It has been known that these markings indicate the level differences resulting from an encounter

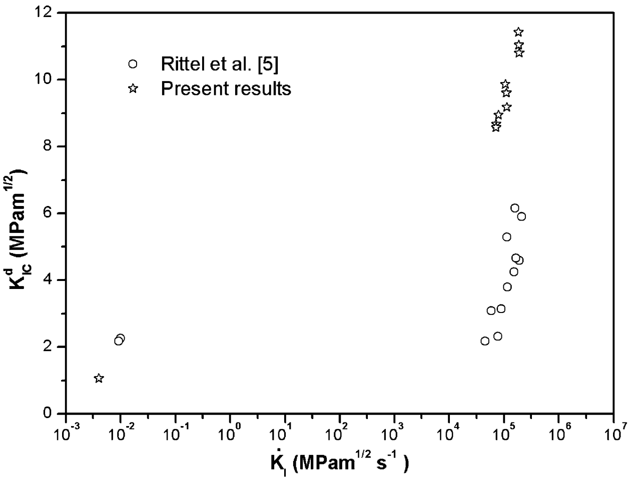

Fig. 5 The variation of crack initiation fracture toughness with loading rates

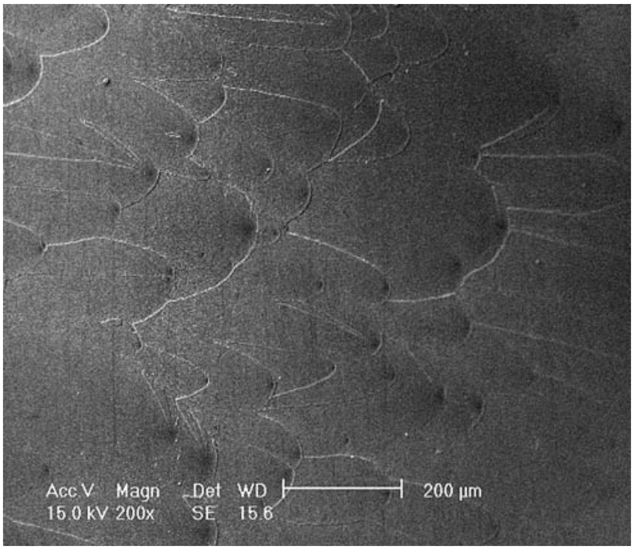

Fig. 6 SEM fractograph taken in the vicinity of the notch front of a dynamically loaded specimen

between a microcrack and a main crack during the main crack propagation [13].

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