FRACTURE BEHAVIOUR OF DUCTILE POLYMER UNDER MIXED MODE LOADING

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ABSTRACT

The toughness of ductile amorphous polymers is affected by crazing and/or shear deformation. The former produces brittle fracture and the other associated with ductile fracture. One deformation mechanism is favored over the other depending on the stress state. In this study, we examined deformation and fracture behavior ahead of the notch tip of a typical ductile polymer (PC). The stress state has been changed widely from a tensile mode (Mode I) to shear mode (Mode II) as well as combined stress states of both modes. Brittle fracture occurred in mode I loading due to the nucleation of an internal craze ahead of shear deformation, whereas mixed mode loading showed brittle-ductile transition behavior as the shear stress component increases. In this transition region, the damage zone at the notch tip is consisted of three regions i.e. shear deformation extended parallel to shear loading direction, internal craze initiated perpendicular to the maximum principal stress direction and ductile crack initiated from the notch tip. As a shear stress component is further increase this internal craze disappeared and ductile fracture occurred due to stable crack growth at the notch tip.

1.INTRODUCTION

The toughness of ductile amorphous polymers is affected by crazing and/or shear deformation. The former generally produces brittle fracture and the other is associated with ductile fracture. One deformation mechanism is favored over the other depending on the stress state, temperature and deformation rate. Under plane strain conditions in which the presence of notches and/or cracks in a thick plate subjected to uni-axial tensile loads, internal crazing occurs ahead of the yielding zone at the tip of a notch or crack, since the constraint of the local plastic zone ahead of the notch tip causes a dilatational stress enough to reah a critical value for craze initiation. Such fracture behavior of ductile amorphous polymers has been extensively studied by Narisawa et. al., changing a number of variables such as temperature, strain rate, thermal history and ambient hydrostatic pressure [1-5]. The ambient hydrostatic pressure directly reduced the dilatational stress at the tip of the local plastic zone so that brittle to ductile transition occurred with an increase of the hydrostatic pressure [5].

However, there are very few studies on the factors which directly control the plastic deformation mode except for the work of Theocaris and Kytopouls[6], who investigated the crack tip blunting of ductile polymer (PC) in the SEM under mixed mode loading. Although they observed three different types of blunting, in particular, the Japanese sword type of blunting under mixed mode conditions, their results were limited to the deformation behavior of the specimen surface.

The purpose of this study is to study the deformation and fracture behavior ahead of the notch tip of a typical ductile polymer: BPA Polycarbonate (PC) under combined stress states of tensile (mode I) and shear (mode II) loading in order to make clear the effects of the stress components on the fracture behavior ductile polymers, by controlling the mode of deformation, i.e., crazing and shear yielding.

2.EXPERIMENTAL

The material used was a commercial grade of BPA Polycarbonate (Panlite, Teijin Co.Ltd.) in the form of 10mm thick sheet. After cutting into a rectangular shape of 20mm width and 120mm length, a round notch of 0.5mm radius was introduced in the center of one edge of the specimen by machining with a convex milling cutter.

These specimens were annealed at 153°C for 24hr and cooled slowly to eliminate the residual strain. Three-point-bending tests were performed for mode I (tensile) condition with a span length of 70mm in an Instorn type-testing machine (Auto Graph, Shimazu DSS-500). Four-point-bending-tests 7,8) as shown in Fig.1 were done for the mode II (shear) condition. The off-center loading was carried out by the same testing jig for the mixed mode loading conditions. The ratio of both loading modes I and mode II was changed by adjusting the distance between the load support and the center of specimen (notch). All tests were made in air at 23°C and 65% relative humidity. For microscopic observations, the thin sections were microtomed parallel to the notch direction at the midsection of the specimen, which was taken out during deformation. The fracture surfaces were also observed by an optical microscope and scanning electron microscope.

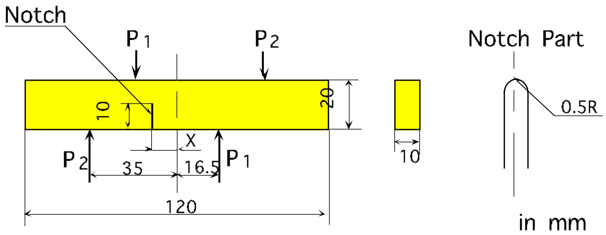

Fig. 1 Shape and dimensions of test specimens

3. RESULTS AND DISCUSSION

3.1 Fracture behavior

Fig 2 shows typical load-displacement curves at a crosshead speed of 1.0 mm/min under mode I, mode II and mixed mode conditions. A load peak due to the onset of crack propagation showed the minimum value under tensile mode and increased with an increasing shear stress component. The crack started in an unstable manner for the mode I loading case, whereas stable crack growth was observed in the mode II loading. In the mixed mode loading conditions the fracture behavior was quite similar to that of mode II loading when the stress ratio of shear to tensile components was larger than 0.67. However, as the stress ratio of shear to tensile components approached 0.3, not only the value of the load peak changed but also both ductile and brittle fracture appeared. Thus, the change of the applied stress from tensile (mode I) to shear (mode II) led to the transition of fracture behavior from brittle to ductile.

3.2Microscopic observations

The polarized micrographs of thin sections of the local deformation region ahead of a notch obtained under mode I and mode II loading conditions are shown in Fig.3. The specimens were unloaded just before the maximum load was reached. The nucleation of an internal craze ahead of the local shear yield zone is observed for the mode I loading specimen. As the applied load was further increased, the internal craze changed to a crack and, eventually, brittle fracture took place. This fracture process was discussed in detail by Narisawa et. al.[9] . On the other hand, both the localized yield zone in the direction of 45 degree from the center axis of the notch and well developed shear bands parallel to the shear loading direction are observed for the mode II loading specimen. The Japanese sword type of

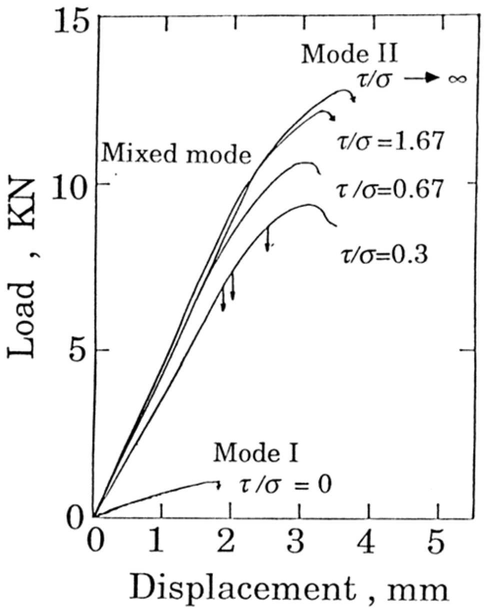

Fig. 2 Typical load-displacement curves of PC under mode I , mode II and mixed mode

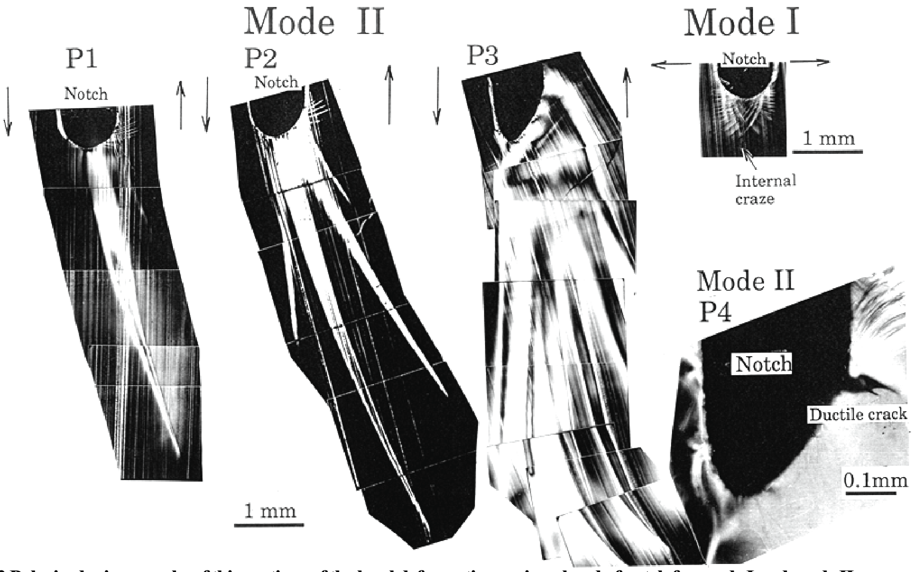

Fig. 3 Polarized micrographs of thin sections of the local deformation region ahead of notch for mode I and mode II loading

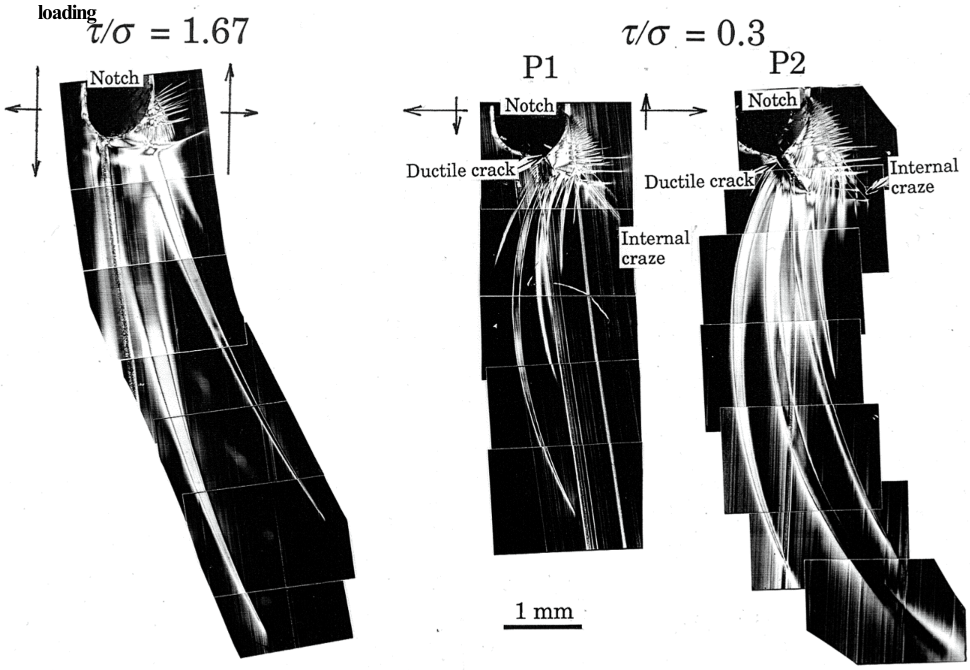

Fig. 4 Polarized micrographs of thin sections of the local deformation region ahead of notch for mixed mode loading

notch blunting is apparent and the localized yield zone becomes obscure with an increasing applied shear load. Finally, a crack initiated at the blunted notch tip and grew in a stable manner perpendicular to the center axis of the notch.

Fig.4 shows the similar micrographs for the mixed mode-loading specimens. The brittle-to-ductile transition behavior was observed as the shear stress component was increased. In this transition region, the local deformation at the notch tip consists of three types of deformation, i.e., the shear deformation bands parallel to the shear loading direction, an internal craze ahead of the localized yield zone perpendicular to the maximum principal stress direction, and ductile crack initiating from the notch tip. The ductile crack propagated in a stable fashion with an increasing applied load and the local shear bands initiated ahead of the internal craze at the same time. As the applied shear stress component was further increased, the fracture behavior approached to that of mode II loading case. In other words, the nucleation of the internal craze was suppressed and ductile fracture occurred due to stable crack growth at the blunted notch tip.

3.3Fractography

The optical microphotographs of the fracture surface for the mode I, mode II and mixed mode specimens are shown in Fig.5. A typical brittle fracture surface which consists of the initiation site of the internal craze around the semicircular smooth region near the notch tip is observed for the mode I loading specimen, whereas a plastic fracture surface [10][11] is observed for the mode II loading specimen. The similar fracture surfaces are observed for the mixed loading specimens fractured at the stress ratios of the tensile to shears components larger than 0.3. Both brittle and ductile fracture surfaces are observed for the specimen fractured at the transition condition of tensile/shear ratio=0.3. These fracture surfaces show the characteristics of ductile fracture. A smooth region around the craze nucleus within the brittle fracture surfaces extends with the increasing fracture load.

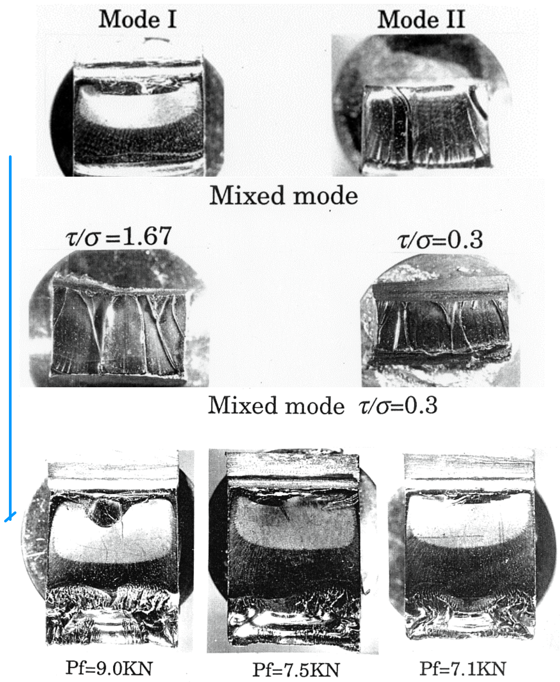

Fig. 5. Optical photographs of the fracture surface for modeI, mode II and mixed mode . Arrow indicates crack propagation direction

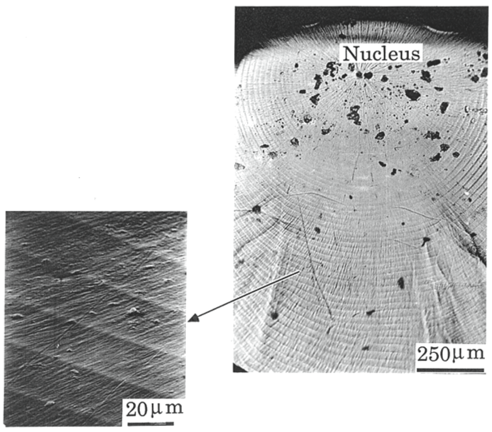

Fig 6 Higher magnified microphotographs around the nucleus site in the transition point of mixed mode (τ/σ=0.3).

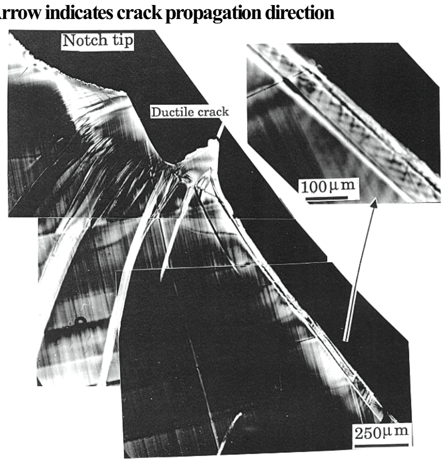

Fig.7 Polarized micrographs of a thinned section of the fracture subsurface of Fig.6.

Fig6 shows higher magnified microphotographs around the fracture nucleus. They showed the tongue shaped feature in the brittle fracture surface at the transition point of mixed loading (tensile /shear ratio=0.3). It can be seen that a clam-shell shaped surface extends from the fracture nucleus and this is similar to fracture characteristics when discontinuous crack growth (DCG) of PC occurs under fatigue loading [12][13]. The band space of about 25μm width for the mixed loading specimen quantitatively agrees with that of DCG, but the fracture surface between the bands is more smooth than that of DCG. Fig. 7 shows the polarized micrographs of a thin section of the fracture subsurface corresponding to Fig.6. Micro-shear bands, in which the space corresponds to the striations, are observed ahead of the localized shear yield zone following an arrested ductile crack. These results show clearly that the formation of striations is caused by the discontinuous growth of the craze and/or crack even under the monotonic mixed loading conditions.

3.4Effect of stress tri-axiallity

The process of brittle fracture in a ductile polymer under mode I loading has been studied in detail by one of the authors 9), who concluded that the dilatational stress produced by the stress triaxiallity ahead of a localized yield zone nucleates the internal craze. The dilatational stress ahead of the notch was given by:

$$\sigma_D = (\sigma_x + \sigma_y + \sigma_z)/3 \qquad (1)$$

Where σ_x, σ_y and σ_z were stress components of axial direction of specimen, notch and thickness, respectively.
If Poisson' s ratio was 0.5

$$\sigma_D = \sigma_z \qquad (2)$$

According to the Hill's slip line filed theory, the σ_y within the yield zone at a distance x from the root is:

$$\sigma_y = \tau_y\{1+\ln(x/\rho)\} \qquad (3)$$

where ρ is the root radius and τ_y is the so-called octahedral critical shear stress for yielding :

$$\tau_y = \{ (\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 \}^{1/2}/3 \qquad (4)$$

The dilatational stress is always taken the maximum at the zone tip:

$$\sigma_D = \tau_y\{1+2\ln(1+R/\rho)\} \qquad (5)$$

where R is a yield zone length .

Thus a critical dilatational stress for nucleating a craze can be evaluated from the location in which an internal craze initiated ahead of the yield zone, and a shear yielding stress can be obtained by the uni-axial tensile test. For example, σ_D/τ_y is 87MPa and the ratio of σ_D/τ_y is 2.17 for slowly cooled PC used in this study. The values of the quenched specimen were slightly higher, 96 MPa and 2.6, respectively [9]. In the mode I test for PC, brittle fracture usually occurs because the maximum ratio of σ_m/τ_0, where σ_m is the mean stress, is about 2.81, which exceeds the ratio of σ_m/τ_0 for the material constant. It is well known that the stress triaxiallity ahead of a crack tip decreases with an increasing applied shear stress. However, there are few studies on the elastic-plastic stress distribution of a cracked specimen subjected to the mixed mode loading. Dong and Pan [14, 15] calculated plane strain mixed mode deformation near the tip of a stationary crack in an elastic-perfectly-plastic Misses solid by the finite element method. They showed that the stress distribution near the crack tip field, when the length of a plastic zone reaches the same certain size for each loading mode. Although our case is different from the cracked specimen, we tried to estimate the change of triaxiallity of a round-notched specimen based on their results. The change of triaxiallity in the mixed mode loading is roughly similar except for the result that the length of localized yield zone observed is quite smaller than that of an initial notch. The result is shown in Fig.8, in which the stress triaxiallity σ_m/τ_0 by solid line plotted against the ratio of an applied stress components τ/σ. The material property is plotted as a horizontal band of σ_D/τ_y . The result reveals that the brittle or ductile fracture observed under mixed mode loading corresponds to the stress triaxiallity ahead of the localized yield zone above or below the stress ratio of crazing to shear yielding, σ_D/τ_y for the material. In other words, the stress triaxiallity is an important factor to determine the fracture behavior of ductile polymers under mixed loading. Crazing is generally more favored in the case of higher stress triaxiallity. However, the situation is complicated at the transition region where the triaxiallity is close to the stress ratio of crazing to shear yielding of the material because the initiation of a craze reduces the stress triaxiallity. The craze is stable and a micro-shear yielding occurs ahead of the tip with an increasing applied load. This raises the stress constraint again, and then the craze starts to grow again. Thus, the process of the discontinuous craze growth continues until the craze reaches a certain length.

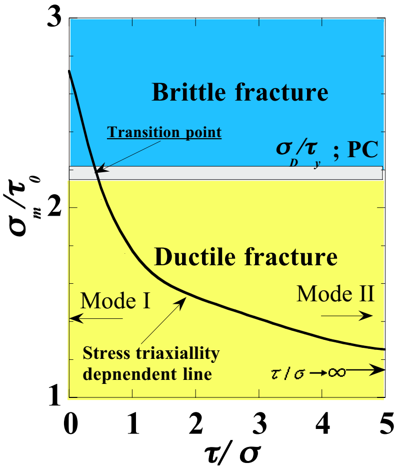

Fig.8 Stress triaxiallity dependence of applied stress components ratio.

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