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Fatigue crack growth of polycarbonate under high pressures

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In order to investigate the effect of hydrostatic pressure on the fatigue crack growth behaviour of solid polymers, an apparatus was designed for maximum pressure of 3000 kgf cm $^{-2}$. The crack growth rates as a function of stress intensity factor range, ΔK, were measured using compact tension specimens of polycarbonate under pressures of 1–2000 kgf cm $^{-2}$. It was shown that (1) the fatigue crack growth rates at pressures higher than 500 kg cm $^{-2}$ were nearly insensitive to hydrostatic pressure, (2) the slope on a log(dc/dN) versus log (ΔK) diagram was higher at the high pressures than at an atmospheric pressure, and (3) shear lips and the tear lines appeared on the fracture surfaces at atmospheric pressure, while they were not observed at pressures higher than 500 kgf cm $^{-2}$.

1. Introduction

Hydrostatic pressure is one of the important factors influencing the mechanical properties of solid polymers. Therefore, the pressure-dependent behaviour of solid polymers, such as elastic modulus, yield stress, fracture stress, etc., has been widely studied by many researchers [1–5] since the pioneering work of Rabinowitz *et al.* [6]. Using a newly devised apparatus, they investigated the pressure dependence of the torsional stress–strain behaviour of polymethylmethacrylate (PMMA), polyethylene terephthalate (PET), and polyethylene (PE) at pressures up to 7 kbar and showed that the shear modulus and the shear yield stress increased monotonically with applied pressure. One of the present authors investigated the cyclic stress–strain curves of PE, polypropylene (PP) and polyoxymethylene to discuss a constitutive equation of solid polymers at pressures up to 2000 kgf cm^{-2} [7, 8], but less attention has been paid to the crack growth behaviour, such as fracture toughness and crack growth rate as a function of fracture parameters. Recently, Takahashi and co-workers [9, 10] investigated the effect of hydrostatic pressure on the Mode I crack propagation at high speed in PMMA and indicated that (1) the crack velocity monitored by ultrasonic fractography decreased with increasing pressure, and (2) there was a morphological change from a cleavage type to a mixed cleavage–ductile type at a fixed pressure.

However, fatigue crack growth data under high pressures have not been measured to date. This is probably because it is difficult to make a testing machine capable of applying cyclic loads to a test specimen whilst keeping a high pressure nearly constant during the test. In the present work, fatigue crack growth behaviour of polycarbonate was measured using a newly developed high-pressure apparatus.

2. Testing apparatus

The home-made high-pressure torsion apparatus used here is schematically illustrated in Fig. 1. The pressure vessel (12) is designed for a pressure of 3000 kgf cm^{-2}. A compact tension specimen (2) held at the grips (3) is subjected to cyclic tensile load. The rotary motion of the axis (8) driven by the servo-motor is converted to the longitudinal displacement by means of the screw (4). The cyclic load is measured through a load cell (1) assembled in the chamber. The load is controlled between the predetermined maximum and the minimum (= 0) loads by a micro-computer. The parts 5-A and 5-B are supported by two rigid side-plates. These plates prevent the rotation of the grips (3). The shaft (8) is supported by two miniature ball bearings put in block 5-B. A needle bearing (6) and a ball bearing (7), which are placed in the cover (11) to relieve the affect of the eccentricity of the shaft (8), make the revolution of the shaft (8) smooth. The details of the cover (11) are shown in Fig. 2. It is designed so that the shaft (8) may be easily inserted into the cover (11) after the specimen is set at the grips. Because the rotary shaft (8) and the axis (9) do not move in the longitudinal direction when the specimen is pulled, the applied pressure is nearly kept constant during the test. The leakage of a pressure medium (turbine oil) is stopped by four O-rings and back-up rings (10). Therefore, fatigue crack growth test is performed under constant hydrostatic pressure without its considerable fluctuation. The pressure medium is turbine oil.

3. Experimental procedure

The material used was a commercial grade of polycarbonate (PC) plate with thickness 3 mm. Compact tension (CT) specimens 30 mm × 28 mm, the dimensions of which were based on the ASTM standard, were

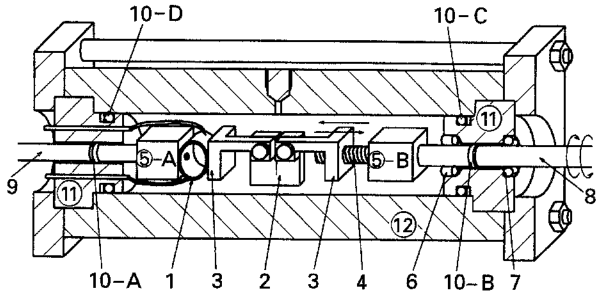

Figure 1 Schematic illustration of the testing apparatus. (1) Load cell, (2) CT specimen, (3) specimen holder, (4) screw, (5) steel block, (6) needle bearing, (7) roller bearing, (8) rotary shaft, (9) fixed shaft, (10) O-ring and back-up ring, (11) inner cover, (12) pressure chamber.

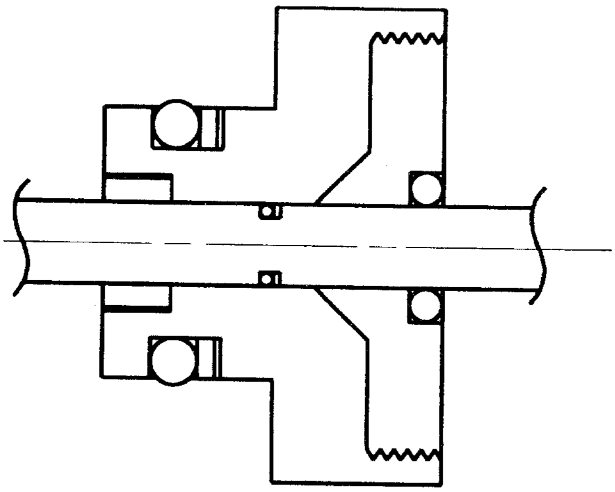

Figure 2 Enlargement of the inner cover.

machined from this plate. After the notch was machined by a fret saw, the natural crack at the notch root was introduced by a home-made machine at a cyclic frequency of about 5 Hz at an applied load less than that for the test mentioned below. The crack growth rate was less than 1×10^{-4} mm cycle^{-1}.

The cyclic tests were conducted at a triangular wave-form between zero and a predetermined maximum load. Because the angular velocity of the shaft (6) is kept constant, the cyclic frequency decreases with increasing crack length. The test frequency is within the range 0.25–0.18 Hz. The tests were executed at room temperature (25 °C) under predetermined pressures of 1, 500, 1000, 1500 and 1900 kgf cm^{-2}. In order to investigate the effect of environmental fluid on the crack growth, tests were also conducted both in air and in turbine oil at atmospheric pressure using large CT specimens, 100 mm × 96 mm.

When a predetermined pressure is suddenly applied to the CT specimen mounted in the equipment through a turbine oil, the temperature rises in the pressure vessel. When the pressure increases to 1500 kgf cm^{-2} in an abrupt manner, the temperature rise amounts to about 10 °C [8]. Because of this temperature rise, the data obtained may depart from the expected ones. Furthermore, both the applied pressure and the temperature rise may affect the output signals of the load cell in the pressure chamber until the temperature decreases to room temperature and the output signals become steady after the lapse of about 30 min. Therefore, the test started after the output signal of the load cell became steady.

Because, after several hundreds cycles, the back-up ring (10-B) sometimes wears away due to the friction between the ring (10-B) and the cover (11) and the pressure medium may leak insignificantly, a small pressure drop in the chamber occurs and, therefore, the output signals measured by the strain gauge may not give an exact load. In this case, after the pressure was reapplied to a predetermined value and the signals of the load cell became steady, the test was continued.

Because the fatigue striations are known to form each load repetition, the crack growth rates ($\mathrm{d}c/\mathrm{d}N$) were measured from their spacings on the fractographs taken from the broken specimen surfaces. For the large CT specimens, the growth rates were obtained from the slopes of the crack growth curves measured by a travelling microscope. The stress intensity factor range, ΔK, was calculated using an equation recognized in a textbook of fracture mechanics. The fracture surfaces were observed by both optical microscopy and a scanning electron microscopy (SEM).

4. Results and discussion

4.1. $\mathrm{d}c/\mathrm{d}N$ versus ΔK

Fatigue crack growth rates, $\mathrm{d}c/\mathrm{d}N$, as a function of stress intensity factor ranges, ΔK, under atmospheric pressure are plotted in Fig. 3 where the open and solid symbols denote the data in air and in turbine oil, respectively. The band shows the range of the data dispersion.

The pressure medium may have some influence on the crack tip for two reasons: (1) the environmental agent used may chemically accelerate crazing, and (2) the viscous liquid penetrating into the narrow crack planes may hydrodynamically alter the pressure distribution along the crack planes due to their opening and closing motion, and hence, may change the stress intensity factor. The pressure increase between the crack planes is supposed to be a function of the opening rate of the crack planes, the viscosity of the fluid, the opening displacement of the crack, etc. For the material (PC) under the present experimental conditions, the effect of the environmental fluid on the fatigue crack growth rate was found to be small, as shown in Fig. 3.

The pressure dependence of the fatigue crack growth rate in the pressure ranges up to 2000 kgf cm^{-2} is shown in Fig. 4, where the band denotes the range of the dispersion of the growth rate data at 1 kgf cm^{-2}. Although the data are considerably dispersed, they may almost fall within a band width. It is found that (1) the crack growth rates at pressures higher than 500 kgf cm^{-2} are nearly insensitive to hydrostatic pressure, and (2) the growth rate under high pressures is slightly lower at small ΔK ranges and higher at large ΔK ranges than that at

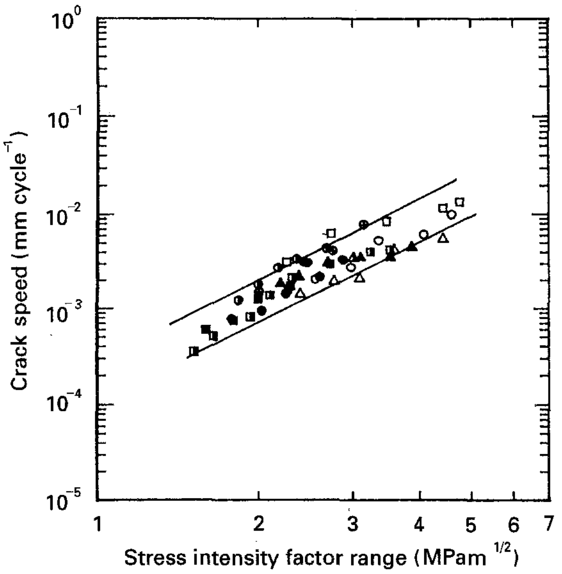

Figure 3 Crack growth rate dc/dN as a function of stress intensity factor range, ΔK, (○, △, □, ◑, △, □, ⊕) in air and (●, ▲, ■) turbine oil at atmospheric pressure.

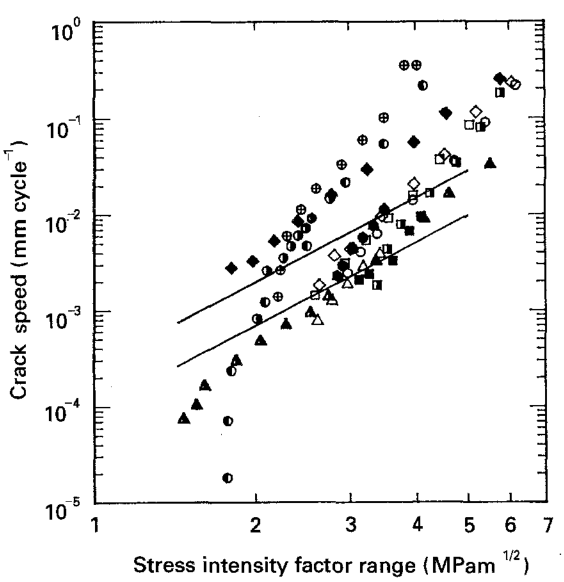

Figure 4 Crack growth rate dc/dN as a function of stress intensity factor range, ΔK, in turbine oil under high pressures of (□, ■, ◫) 500, (△, ▲, △) 1000, (○, ●, ◑, ◐, ⊕) 1500 and (◇, ◆) 1900 $kgf\,cm^{-2}$.

1 $kgf\,cm^{-2}$, and hence, the slope at high pressures on a $\log(dc/dN)$ versus $\log(\Delta K)$ diagram is slightly steeper than that at atmospheric pressure.

4.2. Fracture surfaces

When a crack in a relatively thin plate of polycarbonate (PC) propagates in atmospheric pressure, shear lips may form at the free surfaces. The crack plane is inclined at about 45° to the loading axis as schematically shown in Fig. 5a. The shear lips describe crack growth under plane stress condition and the flat plane corresponds to the plane strain condition. It was shown by a fracture mechanics approach that the shear lip width, w, may be estimated by

$$w = (K/Y)^2/(2\pi) \qquad (1)$$

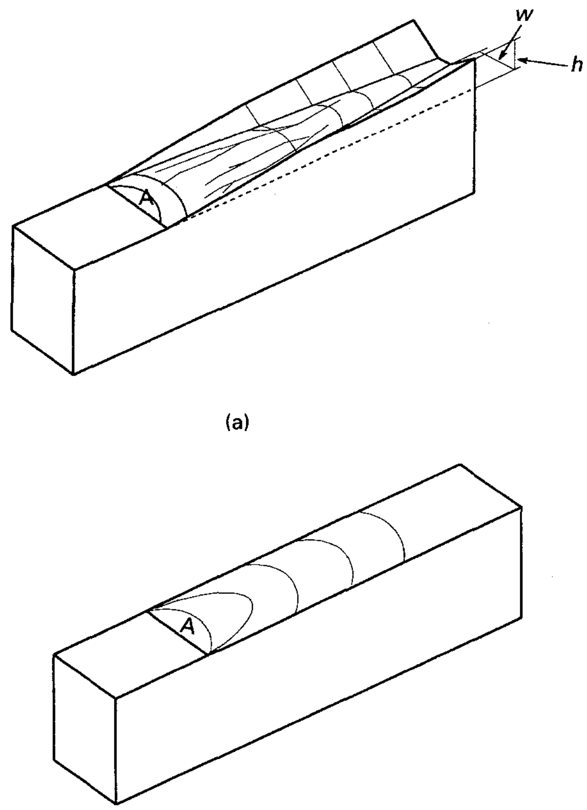

Figure 5 Schematic illustration of fracture surfaces at (a) atmospheric pressure and (b) high pressures. The shear lips and many tear lines along the crack direction are distinctive at 1 $kgf\,cm^{-2}$, while the relatively flat surface continues from the artificial crack tip (A) at pressures higher than 500 $kgf\,cm^{-2}$. w and h are the width and the height of the shear lip, respectively.

where K is the stress intensity factor and Y is the yield stress [11]. In this test, K increases with increasing crack length. In the fatigue samples at atmospheric pressure, therefore, the shear lip width increased with increasing crack length, as expected from the above equation.

It is known that the yield stress, Y, of a solid polymer increases with increasing pressure, P. Hence, at the same K levels, the shear lip width is expected to become small as P increases. The ratio of the yield stress at 1000 $kgf\,cm^{-2}$ to that at 1 $kgf\,cm^{-2}$ is about 1.2 at most in PC. Hence, at the same K level, the shear lip width at 1000 $kgf\,cm^{-2}$ is expected to be about 1.4 times narrower than that at 1 $kgf\,cm^{-2}$. But contrary to expectation from the above equation, shear lips were not observed on the fracture surfaces even at a relatively low pressure of 500 $kgf\,cm^{-2}$, and the fracture surfaces tested at pressures higher than 500 $kgf\,cm^{-2}$ were flat, as shown in Fig. 5b. This may show that the fatigue crack growth at high pressures occurred under the plane strain condition, and hence, there is a mode transition in the fatigue crack growth from a mixed plane stress–plane strain to a plane strain at a fixed pressure. This may cause the difference of the slope of the growth data between at a pressure of 1 $kgf\,cm^{-2}$ and at pressures higher than 500 $kgf\,cm^{-2}$.

Fig. 6 shows the fracture surfaces tested at pressures of 1 and 1000 $kgf\,cm^{-2}$. There exist many fatigue

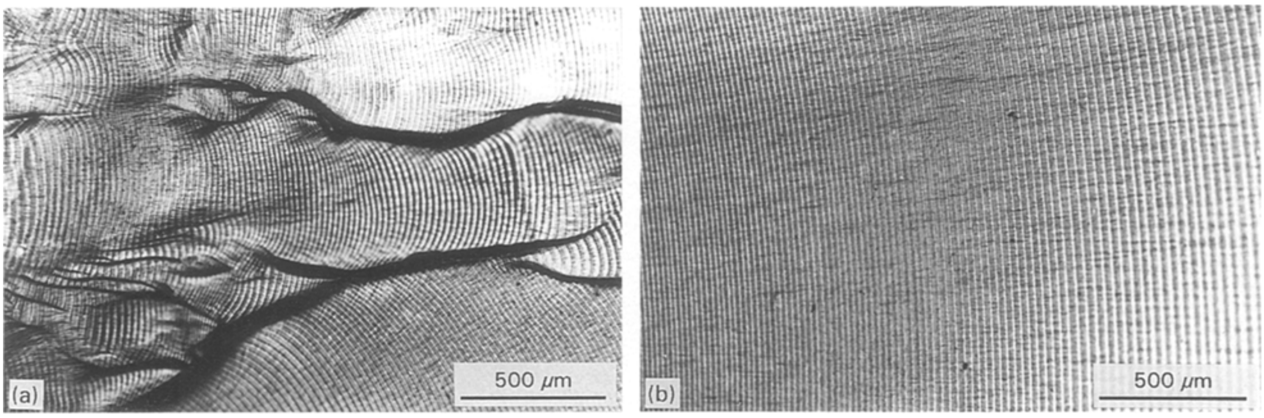

Figure 6 Fracture surfaces at (a) atmospheric pressure and (b) a pressure of 1000 kgf cm^{-2}. The crack growth direction is from left to right.

striations which correspond to the successive positions of the advancing crack front as a result of individual load repetitions. Besides the striations, under atmospheric pressure, the surface is covered with many tear lines along the crack growth direction. But on the surfaces tested at the high pressures, the tear lines abruptly disappeared, exceeding the initial crack introduced in air. In spite of the presence of the tear lines, the shape of the striation seems to be not so affected by hydrostatic pressure. No difference in the shape of the striation was recognized even by SEM observation at high manification.

5. Conclusion

In order to investigate the fatigue crack growth under high pressures, a testing machine was newly developed with the capability for cyclic load to be applied under a constant hydrostatic pressure during fatigue testing. Using this machine, the effect of hydrostatic pressure on the fatigue crack growth rate for polycarbonate was measured. It was found that (1) the fatigue crack growth rate is insensitive to hydrostatic pressure, (2) the tear lines and the shear lips observed at atmospheric pressure disappear at pressures of 500–2000 kgf cm^{-2}, and (3) the shape of fatigue striations is not so affected by hydrostatic pressure.

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