A STUDY OF FATIGUE CRACK PROPAGATION MECHANISMS OF A NON-CRYSTALLINE POLYMER

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ABSTRACT

Fatigue crack propagation (FCP) mechanism of a non-crystalline polymer, using Poly Methyl Methacrylate (PMMA), has been investigated. When cyclic loads are applied to the CT specimens of PMMA, the m values of the Paris regimes were different between the low ΔK(the first stage of the Paris regimes) and the high ΔK(the second stage of the Paris regimes). As well, the fracture surfaces were also different between them. In the low ΔK regime, a mirror-like surface was observed, while at higher ΔK, a rugged surface was observed. The first stage and the second stage were in good agreement with "continuous" and "discontinuous" crack propagation. The fatigue fracture surface was observed by a scanning laser microscope and unevenness of a several micron wide was found on the first stage, just before a rugged surface was appeared.

KEYWORDS

Fatigue crack propagation, non-crystalline polymer, PMMA, the Paris regime, fatigue fracture surface, scanning laser microscope.

INTRODUCTION

Non-crystalline polymers are attractive materials for various applications, as they are low in density and are fabricated by processes such as extrusion, molding and vacuum forming. The applications include window glass of airplanes, thin films, and electric circuit boards.

However, in spite of many important structural applications, the fracture properties of non-crystalline polymers have not been well understood, especially fatigue properties. The fracture properties closely relate to the behavior of crazes, which are planer and defects unlike cracks, and which have load-bearing fibrils. The crazes have a number of fibrils which orient in the parallel direction of external stress. When crazes grow in the direction of width, the fibrils are stretched, and finally break down. Since the behavior of crazes and fibrils are easily observed by various microscopes, much work(Kramer et al, 1978; Sauer et al, 1990) has been done to study their behavior. When the fracture properties were studied, however, only the ideal behavior of crazes and fibrils which were observed by applying the optical interference technique were documented. Very few reports were taken from the other view points.

In the case of fatigue, the attention of researchers has also been concentrated on the relationship between a fatigue crack and a craze of fatigue crack tip. Doll (1983) reported two types of fatigue crack propagation of non-cryatalline polymers from microscopic aspects; "continuous" propagation and "discontinuous" propagation. In "continuous" crack propagation, each loading cycle causes an increment in crack length, while, in "discontinuous" crack propagation, the crack tip remains stationary for many loading cycles and then at some particular cycle it advances by an increment. Craze geometry at a crack tip in each propagation has been measured, however, it has rarely been considered that each propagation was located for the whole process of fatigue fracture. The mechanism which causes "discontinuous" crack propagation has not been known.

We have studied the relationship between the fracture surface appearance and the macroscopic aspects of fatigue crack propagation, and have tried to determine the dominant factor in stable fatigue crack propagation. It is important to notice not only local phenomena but also the whole process of fatigue fracture to determine fatigue crack propagation mechanism of amorphous polymers such as PMMA.

SPECIMEN PREPARATION

For this study, compact-tension specimens (W=50mm, B=20mm) made of PMMA (Acrylite; Mitsubishi Rayon Co., Ltd) were machined from a cast sheet. This PMMA had a number-average molecular weight of 1,430,000. All the specimens were carefully cleaned in pure water using an ultrasonic washer, and were annealed at a temperature of 360K for 72 hours. Each specimen had been stored in desicators at a temperature of 293K and a relative humidity of either 12, 34, 55, 75 or 93% for more than 3 years, before the tests. Water content increases with an increase in the relative humidity in which the specimens are stored. The humidity in each desicator was controlled using a saturated salt solution method which is the best way to keep closed space in constant humidity for a long time. A range of humidities was investigated in order to correlate the effect on the fracture surface and the microscopic aspects of fatigue crack propagation.

EXPERIMENTAL

The experiments were carried out under the same environmental condition as the environment in which the specimens had been kept, which was either 12, 34,55, 75 or 93%RH (relative humidity). Figure 1 shows a diagram of the experimental apparatus. The humidity in the test cell was kept constant with an accurate humidity generator, which provided a mixture of dry and wet air at a certain rate, during the fatigue test. A temperature and humidity tracer was used to monitor the environmental condition in the cell. Load and the back strain of the specimens were recorded with a data logger at regular intervals. These specimens were subjected to uniaxial cyclic tension with a servo hydraulic testing machine at a sinusoidal frequency of 1 Hz, a load ratio R of 0.1 and a load amplitude of 132.4N. The crack length was measured using both the compliance method and a traveling microscope. Crack propagation data were analyzed to compare the macroscopic FCP per cycle, da/dN, with the stress intensity factor range at the crack tip, ΔK. When ΔK-da/dN was plotted on a log-log plot, linear Paris regimes were observed, that is, each of them was expressed as follows;

$$da/dN=A(\Delta K)^m$$

where m is the slope on log-log plots of da/dN-ΔK and A is a constant.

Fractographic studies were conducted on an Scanning Laser Microscope (SLM; Laser Tech Co., Ltd.) with He-Ne Laser, which had a wave length of 632.8nm and a resolution of 0.015μm. The merits of this SLM are as follows; one is that polymers can be directly observed without vacuum deposited layers which are needed when polymers are observed using a scanning electric microscope and two is to be able to measure surface roughness without touching the sample.

RESULTS AND DISCUSSION

Figure 2 shows the results of the FCP tests under the same environmental condition as the environment in which the specimens had been kept in 12, 34, 55, 75 and 93%RH, respectively. It is found that the relationship between the FCP resistance and the water content is somewhat complex. The increase in water content in a low humidity (below 50%RH) has almost no effect on the FCP resistance, while that in high humidity (over 55%RH) enhances the FCP resistance. Each curve of Fig. 2 has an inflection point in the middle of the Paris regime at da/dN of $7\times10^{-7} \sim 1\times10^{-6}$ m/cycle. We call the regime before the inflection point the first stage and that after the inflection point the second

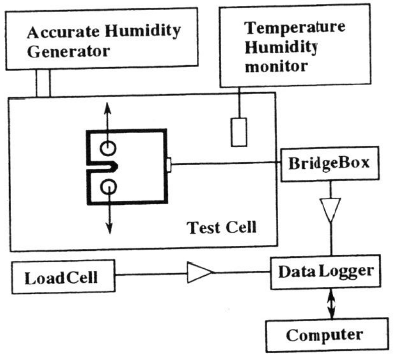


Fig. 1 Diagram of experimental apparatus

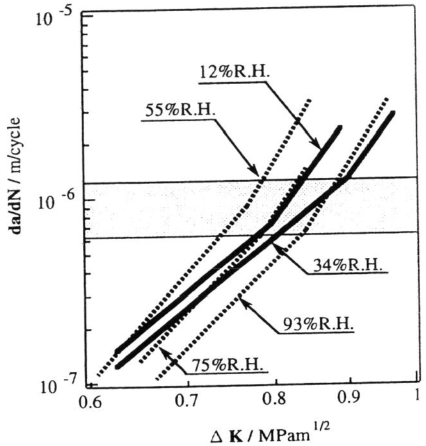


Fig. 2 The effect of humidity on the fatigue crack propagation in PMMA; the shaded area in the figure indicates a region in which inflection points of the m value of Paris resime exist.

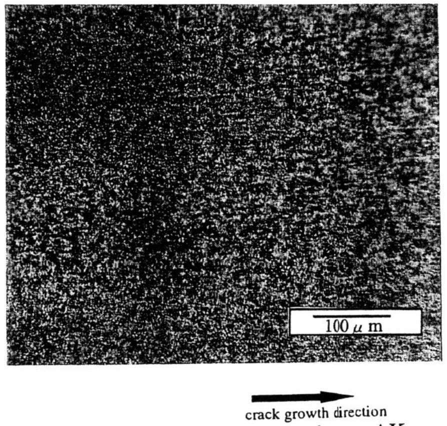


Fig. 3 Fracture appearance at a lower ΔK, this is a mirror-like plane (humidity condition is 12%RH)

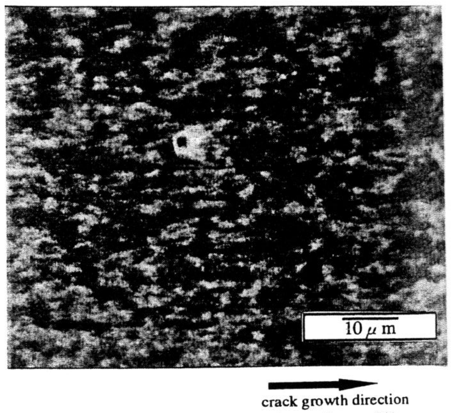


Fig. 4 Unevenness on the mirror-like surface (humidity condition is 12%RH)

stage. Table 1 shows a summary of m value of each curve in Fig. 2. In the first stage, the m values in low humidity are smaller than those in high humidity.

The m values on the first stages are in a range between 6.3 and 8.5, which values seem to depend on sorbed water content. While, m values on the second stages are approximately constant. This suggests that the FCP properties on the second stage may be the intrinsic characteristics of the material, that is, the m value is independent of the amount of sorbed water.

Doll (1983) reported about two types of fatigue crack propagation from the microscopic aspects; "continuous" propagation and "discontinuous" propagation. It has not been known whether the first stage and the second stage on a log-log plot of da/dN-ΔK agree with "continuous" propagation and "discontinuous" propagation or not.

Therefore, we carried out fractographic observation using the SLM. Figure 3 shows the typical fatigue fracture surface at a lower da/dN in every humidity condition. In the macroscopic observation, almost all the fracture surface at a lower da/dN is a mirror-like plane, while in the microscopic observation using the SLM, the fine random pattern is found on the fracture surface. The roughness of this fracture surface is below 2 or 3 μm. These suggest that a crack propagates gradually in every cycle, cutting the middle of the enough grown-up fibrils of the crazes at the crack tip. This crack propagation is the "continuous" one. However, when we observed the whole mirror-like surface in detail, tens of uneven points were randomly found on the fracture surface of the first stage. Figure 4 shows an example of these points and these will be discussed later.

At a higher da/dN, a typical fatigue fracture surface is shown in Fig. 5. It was found that the fracture surface has very rough gaps in the direction of both the parallel and the right angle for the FCP and also that it has regular jumping patterns. These suggest that a crack propagates after every several hundred fatigue cycles. This crack propagation is the "discontinuous" one. The roughness of the fracture surface is more than 50 μm. When we consider the process of fatigue fracture, the rough gaps unexpectedly appear at certain points on the fatigue crack flont line, and the fracture surface is covered with such rough area, and finally the material breaks down unstably. Such a progress of the fracture surface formation is common to all the fatigue crack propagation tests.

Figure 6 shows the relationship between the macroscopic ΔK and the proportion of rough area. This shows that the fatigue crack propagation curve folded on the transitional area where the rough surface on the mirror-like one appears, that is, the first stage and the second one were rough agreement with the "continuous" propagative area and "discontinuous" one. Generally when a crack propagates as a zig-zag for the direction of FCP, the macroscopic propagation rate decreases, because of the decrease in the ΔK_{eff}. However, here is not so. This shows that the mechanism of the "continuous" fatigue crack propagation is different from that of the "discontinuous" one.

Some workers have explained that the "discontinuous" propagation occurred at more than a certain da/dN, however, as shown in Fig. 6, both the "continuous" regime and the

relative humidity (%RH)	m values	
	the first stage	the second stage
12	6.3	10
34	6.3	10
55	8.5	12
75	8.1	12
93	8.0	12

Table 1 m value of Paris regime of each curve in Fig. 2

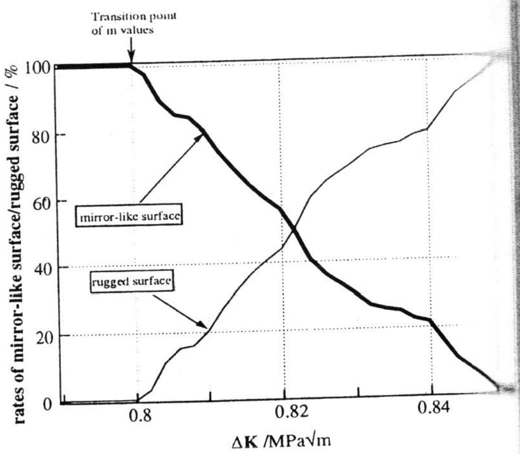
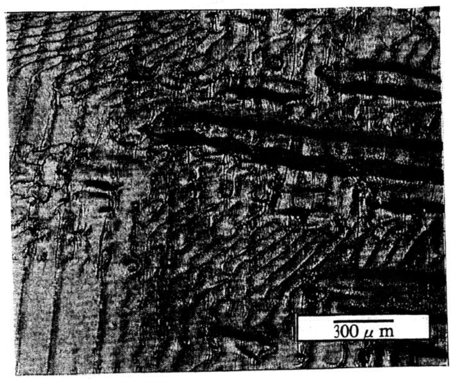
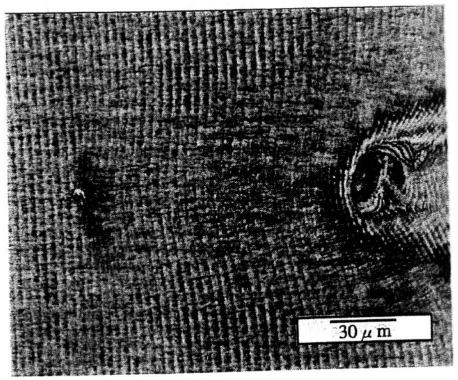


Fig. 6 The relationship between the ΔK and the rate of the rugged surface (humidity condition is 12%RH)



crack growth direction

Fig. 5 Fracture appearance at a higher ΔK, this is a rugged surface.
(humidity condition is 12%RH)



crack growth direction

Fig. 7 A trigger point for the rugged surface (middle and left side) and onset of the rugged surface (middle and right side)
(humidity condition is 12%RH)

"discontinuous" regime coexist for some stress conditions. This shows that a da/dN is locally accelerated in the "discontinuous" regime. However, it has not been known what was the factor which causes "discontinuous" crack propagation. Therefore, we examined the onsets of the "discontinuous" propagation. Figure 7 shows an initiation site of the discontinuous propagation. All the tips of the "discontinuous" propagation had a point like this. We call this point a trigger which is the microscopic aspect of the mechanism which causes "discontinuous" crack propagation. This trigger may lead to stress relaxation for the neighboring material, because the optical interference fringe pattern shown by the laser beam of the SLM occurs and the striations are curved, just after the point. The fatigue crack propagation rate after the point is locally higher, and after that, "discontinuous" propagation started. Compared with the same trigger points on both sides of the fracture surface, the points were found to be either projections or holes and to be a good fit each other well-like making fracture surface. It is obvious that the trigger point is not a void. Also these points sometimes appear on the fracture surface of "continuous" propagation, as previously mentioned in Fig. 4. The size of this point is 5~7μm in width and 0.1~1μm in depth. It can also be thought that a trigger point is created due to a local rise of the temperature. However, as a result of the measurement of the temperature at the crack tip during the fatigue test, the temperature was found to be almost constant. It is possible that a trigger point is caused by inhomogenious nature of the material, for example an inclusion or a bundle of molecular chains. This suggests that the "discontinuous" propagation occurs if a trigger point exists when ΔK exceeds a certain value. However, the nature of this trigger point has not been analyzed yet in detail. Further study is necessary on this issue.

CONCLUSIONS

1. The first stage and the second stage on a log-log plot of da/dN-ΔK well agree with "continuous" propagation and "discontinuous" propagation.
2. It was found that tens of rough points, that is, trigger points, which are either projections and holes, are randomly distributed on the fracture surface.
3. The "discontinuous" propagation may occur if a trigger point exists when ΔK exceeds a certain value.

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