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EFFECTS OF STRESS RATIO ON STRIATION FORMATION UNDER CYCLIC LOADING CONDITIONS IN POLYMETHYL METHACRYLATE (PMMA)

C. Ishiyama*, M. Kobayashi, T. Asai and Y. Higo

Precision and Intelligence Laboratory, Tokyo Institute of Technology,
4259 nagatsuta-cho, Midori-ku, Yokohama, Kanagawa, JAPAN

ABSTRACT

The fatigue crack propagation tests were performed on an amorphous polymer, poly (methyl methacrylate) (PMMA) to investigate the striation formation mechanisms. A confocal scanning laser microscope was used to observe in-situ crack propagation in compact type (CT) specimens under tensile-tensile fatigue loading conditions. Fatigue cracks usually propagated within the craze which always existed at the crack tip at a relative humidity of 75% and an R-ratio of 0.1-0.5. Craze fragments were observed at the edges of the crack at the maximum load of a loading cycle. However, they disappeared in the subsequent cycle at the R-ratios. This may be because a part of the broken fibrils, which were situated just behind the crack tip, were pushed down by the contact between the fracture surfaces during unloading. This may mark fracture surfaces with striations. However, broken crazes did not disappeared in the subsequence cycle at an R ratio of 0.7. After these tests, fatigue fracture surfaces were observed using a field emission-gun scanning electron microscope (FE-SEM). With increasing R-ratio, striations become less obvious. These results support the contact model for striation formation. According to these results, a striation formation mechanism on PMMA is discussed.

KEYWORDS

striations, polymethyl methacrylate (PMMA), fatigue crack growth, stress ratio

INTRODUCTION

Recently many researchers have been studying crack propagation behavior of glassy polymers under static loading conditions [6, 12] or cyclic loading conditions [2, 3, 9-11] to clarify the mechanisms of crack propagation.

Crack propagation is strongly affected by plastic deformation at the crack tip and the typical plastic deformation of polymethyl methacrylate (PMMA) is crazing. In our previous study, the vicinity of a crack tip, which was growing in PMMA, was observed in detail using a scanning laser microscope. It was found that the crack usually accompanied a craze and bright bands, which were made of broken craze, were remained along the crack wakes under monotonic loading conditions. Fracture surfaces were even in this case.

However, these bands were not observed under cyclic loading condition but successive ridges were sometimes observed along the crack wakes. Striations corresponded with the valleys between these successive ridges. These results suggest that striations were made by contacts between surfaces during unloading, in other words, closure produces striations on fatigue fracture surfaces of PMMA.

To clarify the effects of closure on striation formation in PMMA, fatigue tests were performed with changing stress ratio. A confocal scanning laser microscope was used to observe in-situ fatigue crack propagation in compact type (CT) specimens. These observations clarify the state of the crack wakes in PMMA at each stress ratio. Moreover, to clarify the effects of R-ratio on striation formation, fatigue fracture surfaces were observed using FE-SEM.

According to all the results, both of a striation formation mechanism and a crack propagation mechanism on PMMA are discussed.

MATERIAL AND EXPERIMENTAL PROCEDURES

Material

The material used in this study was a commercial acrylic cast sheet, 15 mm in thickness, Sumipex supplied by Sumitomo Chemical Co., LTD. Compact type (CT) specimens with dimensions shown in Figure 1(a) were cut from this sheet.

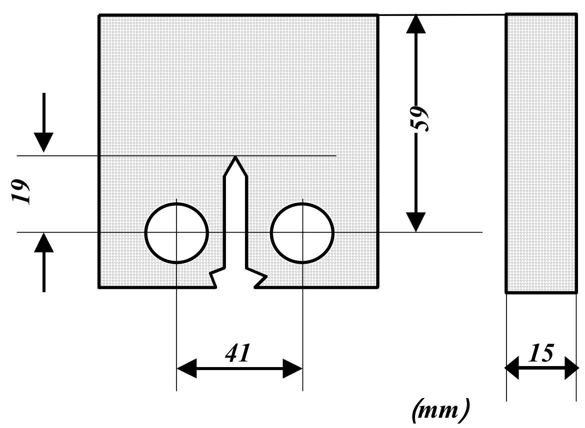


Figure 1: A schematic diagram of a compact type(CT) specimen

The specimens were heat-treated in an oven at a temperature of 363 K for 24 hours to dry and remove any residual stress.

Prior to the tests, the specimens were kept under a 75% relative humidity condition at a temperature of 293 K for the purpose of adjusting the water content in the specimens, because the humidity condition is optimal for stable crazes growth according to our previous studies [4-5]. All the specimens had been stored in the humidity until the water content in the specimens saturated with the humidity, for more than a year [1].

Experimental procedure

A fatigue testing machine, which can be installed on a scanning laser microscope (SLM) (made by Lasertec Co., Ltd.), has been developed to observe in-situ the crack tip shape on a side surface. The details of the machine are shown in Fig. 2. An ultrasonic motor drives a screw to apply load on a specimen.

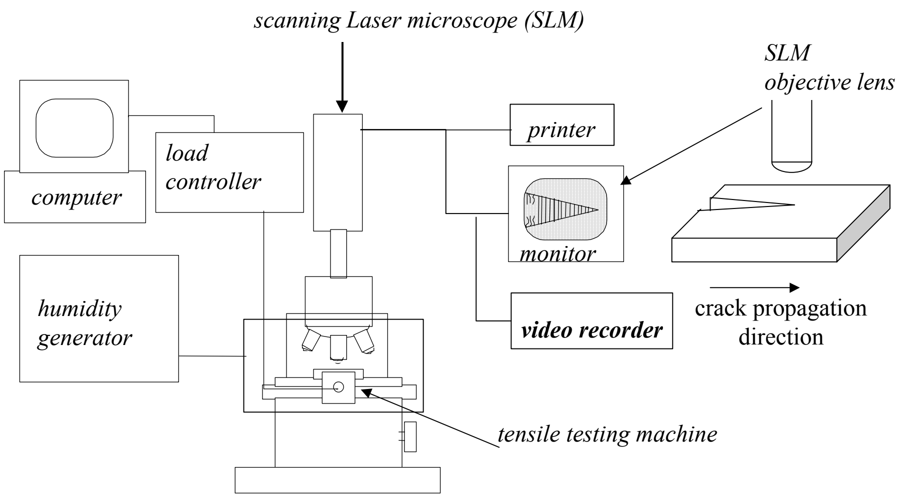


Figure 2: In-situ observation using scanning laser microscope(SLM)

Prior to the crack propagation tests, pre-cracks of 1mm had been introduced to the specimens under a cyclic loading condition (at a mean stress intensity factor (K_{mean}) of 0.26 $MPam^{1/2}$, at an R ratio of 0.1 and at a sinusoidal frequency of 1 Hz).

Tensile load was applied to a specimen until the main crack started to grow and then the load was decreased until the crack stopped growing. This threshold stress intensity for a monotonic loading was defined as K_{th}, which was 0.78 $MPam^{1/2}$, in this study.

Seventy percent of K_{th}, 0.55 $MPam^{1/2}$, was chosen for the maximum stress intensity factor (K_{max}) for the fatigue crack growth tests. Fatigue tests were performed at K_{max} of 0.55 $MPam^{1/2}$- using triangle waves at a frequency of 0.01 Hz and at stress ratios of 0.1, 0.3, 0.5 and 0.7, to clarify the effect of closure on the formation of striations on fracture surfaces. The vicinity of fatigue cracks was observed on a side surface of a specimen with changing R-ratio and the images were recorded using the a video recorder.

After the in-situ observations, the PMMA specimen was broke in two by overloading without unloading to observe the fatigue fracture surface. The fracture surfaces of the specimens were sputter-coated with osmium and observed using a field emission-gun scanning electron microscope (FE-SEM).

RESULTS AND DISCUSSION

In-situ observation on propagating fatigue crack in PMMA

In this study fatigue crack mostly grew into the craze accompanied the crack and the craze was broken at the midrib. This suggests that fracture surfaces were covered with the fragments of the craze. Previous studies [7, 14] also pointed out that fracture surfaces in PMMA must have thin fracture layer, which was demonstrated by on the evidence that color interference fringes observed on the surfaces.

At low R-ratios of less than 0.5, however, fragments of the craze were hardly observed at the edges of the fatigue crack wakes. In further detail, when the crack just propagated at K_{max} in a loading cycle, fragments of the craze had still remained at the edges of the crack just behind the crack tip, but the fragments disappeared in the subsequent cycle. This may be because the craze fragments were pushed down by contact between the fracture surfaces, in other words, crack closure.

On the other hands, at an R-ratio of 0.7 the fragments remained at the edges of crack wakes after the subsequent cycles. Figure 3 shows the vicinity of the fatigue crack tip after the R ratio was changed from 0.5 to 0.7. This micrograph makes it clear that the craze fragments along the edges of the crack wakes disappeared at an R-ratio of 0.5 but remained at an R-ratio of 0.7. This result shows that closure should collapse the craze fragments layers on fatigue crack propagation in PMMA.

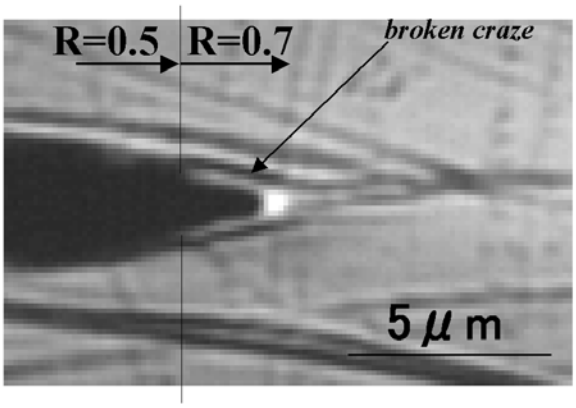


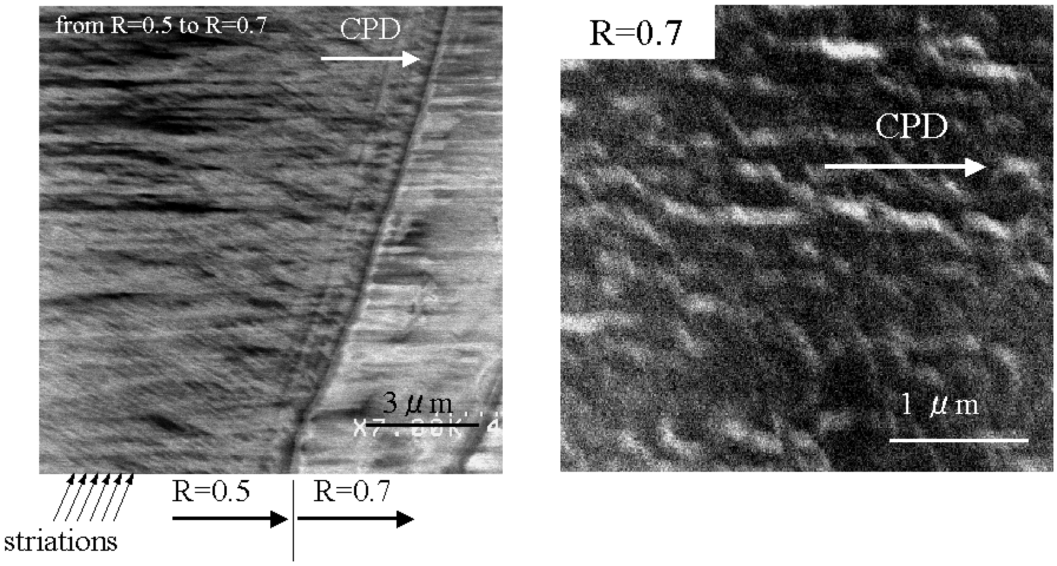
Figure3: A micrograph of a fatigue crack tip, after the stress ratio was changed from 0.5 to 0.7

Striations on the fatigue fracture surface in PMMA

In our previous study [15] we suggested that striations on fatigue fracture surfaces in PMMA might be formed by the contacts between fracture surfaces. This means that it is correct, pushing down the craze fragment layers in each cycle would make a striation.

In FE-SEM observations, striations become less obvious on the fracture surfaces in the material with increasing R-ratio. Figure 4 (a) shows a fatigue fracture surface at which R ratio was just changed from 0.5 to 0.7. At an R-ratio of 0.5 striations, which are partly shown by several arrows in the figure, were narrowly observed, but were not observed at an R-ratio of 0.7 in spite of high magnification as shown in figure 4 (b).

These FE-SEM observations also support that the contact between fracture surfaces should make striations on fatigue fracture surfaces.



(a) when a stress ratio was changed from 0.5 to 0.7

(b) tested at the stress ratio 0.7

Figure 4: Micrographs of fatigue fracture surfaces

From these results a striation formation mechanism is proposed as follows. A fatigue crack propagates into the midrib of the craze accompanying the crack during a loading of a half cycles and new fracture surfaces are covered with these craze fragments. Then, the crack is closing with unloading of a half cycles and the craze fragments are pushed down by the closure in each cycle. Pushing down the craze fragments in each cycle produce the striations on the fracture surfaces.

Fatigue crack propagation mechanism

A crack does not propagate at a constant K_{max} condition, However, when the load is unloaded and reloaded a crack propagates. This may be because the craze fibrils of the crack tip become weak by unloading and/or reloading. Several researchers [8, 13] suggested that craze fibrils at the crack tip were entangled each other by unloading. This suggests that the critical length for failure of entangled fibrils might become shorter than the fibril length at K_{max} in the previous cycle. The entanglement of fibrils in the craze is one of the possible mechanisms for fatigue crack growth. There is another possible mechanism, which is creep deformation. The strength of the fibrils might decrease by creep deformation, because PMMA is a visco-elastic material. However, the crack did not propagate when the applied load was kept at K_{max} for more than half an hour. Thus, it is difficult to conclude that the creep deformation of fibrils is the main cause of fatigue crack growth in PMMA. It is thus considered that the main cause should be resulted from unloading and/or reloading, for example, the entanglement or any other cause for decreasing the strength of craze fibrils.

CONCLUSIONS

Crack growth behavior in PMMA was investigated by in-situ observation under a scanning laser microscope to clarify the crack propagation process under cyclic loading conditions. The following conclusions are reached;

1. A fatigue crack propagated into the midrib of the craze during loading in each cycle. However, the craze fragments did not remain at the edges of the crack wakes. This may be because the craze fragments on fracture surfaces were pushed down by crack closure and striations on fracture surfaces should be formed due to the closure.
2. The strength of the craze fibrils at the crack tip might become lower than that of the previous cycle. It should be due to the weakened fibrils by closure between fracture surfaces. The fibrils might be weakened mainly due to the entanglements of fibrils.

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