

QUASI-STATIC CRACKING OF PMMA IN HOSTILE ENVIRONMENTS

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Despite the increasing use of PMMA in structural engineering design, relatively little work has been done in the past to investigate the effects of absorption of hostile environments at the crack tips on the fracture toughness R of this material. The present report discusses some of the more important aspects of fracture behaviour of PMMA in hostile organic solvents.

Generally, even for the short time scale of our experiments, absorption of solvents at the crack tips will produce appreciable swelling in the local material. Consequently, both the fracture toughness R and the local stress intensity factor K will vary with the quantity of the environmental species absorbed. Swelling is a time dependent process, and experimental observations recorded in [1] show a distinct hardening and softening phenomenon of the local material at the crack tip region. In support with the argument put forward in Gurney and Hunt [2], hardening gives rise to an increase of material fracture toughness R and subsequent softening produces a reduction in R . Instability is usually associated with the crack running into this locally softened material. Thus, for tests performed in machines with monotonic increasing displacement, i.e., $du/u > 0$, no reliable measurement of the fracture toughness of PMMA cracking in hostile environments has been recorded so far in literature. However, successful quasi-static cracking experiments have been realised by carefully controlling the motion and growth of the swelling zone with a suitable combination of test piece geometry and cross-head displacement rate \dot{u} so that the crack continuously runs into the swollen material with a high fracture toughness R . It would thus be very surprising that the material assumes a tougher resistance to cracking in the hostile environments.

In our experience, stable cracking experiments may be obtained easily by using either a favorable test piece geometry, or the adoption of suitable external stabilizers [1,3,4]. Table 1 gives a list of R values of PMMA against appropriate environmental fluids as obtained by these methods. Figure 1 shows the results of the stable cracking experiments in which 1/4 in thick PMMA plates were fractured in a 99% CCl_4 solution and in air at reference conditions of 42% R H and 23 deg C. the cross-head displacement rate of the Instron was 0.01 cm/min. The fracture toughness R in CCl_4 is found to be 0.560 Kg/cm which is about 1.5 times that in air (0.366 Kg/cm) at comparable crack front velocities (0.5-0.8 cm/min).

As for crack initiation, the presence of the hostile environmental fluids usually lowers the material crack initiation resistance. This reduction is probably proportional to the relative aggressiveness of the solvents to the material. Figure 2 generates a series of R -loci for crack initiation in PMMA using a 1/4 in thick Outwater double

torsion specimen. To avoid any residual stresses left after machining, programmed annealing was done prior to the test runs. The occurrence of crazes was also minimised by a coating of silicone oil onto the specimen surfaces. Experiments also show that the crack initiation resistance is exponentially dependent on the cross-head displacement rate. From these experimental results, it is apparent that organic solvents are detrimental to PMMA in crack initiation but certainly beneficial in crack propagation.

Static fatigue of PMMA has also been investigated. By using a simple but clever crack propagation apparatus devised by Prof. C. Gurney, reported in [1], we have been able to measure, at sustained displacement, the quasi-static crack growth of PMMA when immersed in hostile organic solvents as a function of time. To prevent excessive creeping, glass plates were glued onto the specimen surfaces. Table 2 gives a comparison of the fracture toughness R of PMMA when immersed in various solvents. The crack speeds are also included for reference.

Cyclic fatigue of PMMA in organic solvents is a relatively less explored domain. Basically, the crack growth rate per cycle may be related by the following equation,

$$d(2L)/dN = C(\Delta R)^m \quad (1)$$

where C is a material constant depending on the environmental fluid, cycling frequency and mean load; m , an exponent invariant in cycling frequency; and ΔR , the crack-extension resistance range. Figure 3 shows a typical fatigue crack propagation result of PMMA in organic solvents. In our fatigue experiments, center-notched plates were cycled with zero-tension stress ranges at predetermined frequencies. In general, the complete crack growth may be divided into three stages. Stage 1 crack growth rate is associated with the generation of minute crazes around the crack tip region so that the growth per cycle is reduced as the crack-extension resistance range is increased. However, by proper annealing of the specimen before the test run this nucleation of crazes may be minimised or even eliminated. In stage 2 crack growth, where $d(2L)/dN$ increases with ΔR , the rate is determined by the interaction of the stress-strain field and the absorbed fluid near the crack tip region. It should be noted that a slope transition exists before the onset of stage 3 crack growth where the rate is more mechanically controlled than is environmentally assisted. This slope transition invariably occurs at a range of ΔR values of 0.38 - 0.42 Kg/cm which corresponds well to the fracture toughness of PMMA tested under atmospheric conditions. Table 3 gives the relative magnitudes of m for the last two stages of crack propagation in PMMA against given organic solvents.

In fact, when the fatigue experiments were not exposed to any organic solvents, no slope transition was observed. Also, in the course of these experiments, we have evidenced a very interesting crack closure effect due to crack tip residual stresses when the test piece was left overnight or allowed a rest period. Apparently, this results in a delay or retardation of crack growth rate when the ex-

periment is resumed.

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Table 1

Comparison of R of PMMA in Environmental Fluids
(Data Obtained From $du/u > 0$ Tests)

<u>Environmental fluid</u>	<u>R (Kg/cm)</u>
Air	0.38 - 0.42
Lubrication oil	0.544
CCl ₄ (99%)	0.56 - 0.65
Tap water	0.65 - 0.70

Table 2

Comparison of R of PMMA in Environmental Fluids
(Data Obtained From Sustained Displacement Tests)

<u>Environment</u>	<u>Test runs</u>	<u>R(environment)</u>	<u>L(cm/hr)</u>	<u>R(air)/R(env)</u>
Benzene	16	0.010	0.58	40
Ethanol (95%)	13	0.018	0.20	25
CCl ₄ (99%)	10	0.053	0.08	10
Octane	5	0.256	0.80	1.75

Table 3

Value of Exponent m in Fatigue Crack Propagation Law For PMMA

Environmental fluid	Stage 2	Stage 3
Air	2-2.50	2-2.50
Ethanol (95%)	6-7.00	3.5-4.5
CCl ₄ (99%)	6.5-7.15	2-2.50

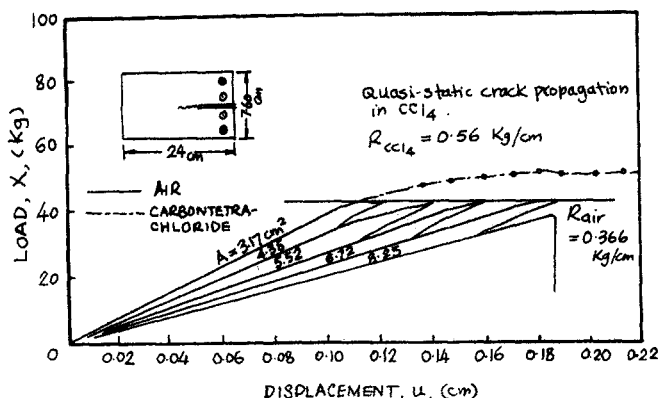


Figure 1. Quasi-static cracking of PMMA in air and in CCl₄ by bending.

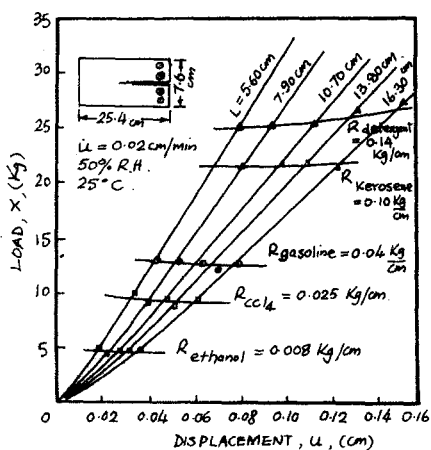


Figure 2. Crack initiation resistance of PMMA in various environmental fluids.

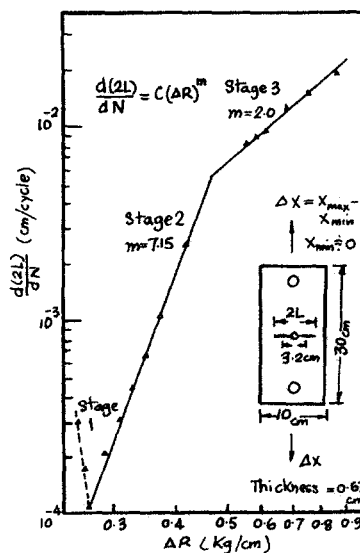


Figure 3. Fatigue crack growth of PMMA in CCl₄ at 17 cpm.