On the environmental fracture of polymethylmethacrylate

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Crack propagation of PMMA in some liquid environments is described for various testing conditions, such as fixed load, fixed displacement and monotonically increasing displacement. Fracture mechanics concepts have been used successfully in analysing the results. When continuous stable cracking is achieved, values of fracture toughness ($R$) for PMMA under these loading conditions are obtained as a function of crack velocity ($\dot{L}$) using the method of Gurney and Hunt [11]. For crack velocities greater than $10^{-2}$ mm sec$^{-1}$, the fracture toughness values in the environments are increased when compared with the corresponding air results. Unique relationships between $R$ and $\dot{L}$ have been shown to exist for cracking in ethanol and carbon tetrachloride.

1. Introduction
Fracture of PMMA in hostile environments is an interesting but complex problem. Previous papers on the subject are those of Andrews and Bevan [1, 2], Andrews and Levy [3] and Marshall et al. [4].

The ability of certain liquids to cause swelling and hence softening of glassy plastics such as PMMA is well known. Crazes are formed when the softened material undergoes cavitation due to a sufficiently high dilatant stress [2, 3 5]. "Compatible" liquids can cause remarkable reductions in the glass transition temperature ($T_g$) and hence lower the stress necessary for craze formation. For relatively "incompatible" liquids, appreciable swelling may also occur at stress concentration sites such as flaws and cracks where a large local dilatant stress exists [6]. As an example, Fig. 1 records some experimental results [7] showing the remarkable reduction of microhardness of PMMA at the crack tip region due to softening by the liquid environments.

The mechanics and mechanisms controlling craze and crack propagation in edge-cracked PMMA tensile specimens immersed in a variety of liquids have been discussed in [1-4]. Using fracture mechanics criteria, a minimum surface energy requirement ($\gamma_0$) [1, 2] or equivalently a threshold stress intensity factor ($K_m$) [4] for crack propagation or craze formation may be obtained by measuring the critical applied stress ($\sigma_c$) necessary to cause a discontinuity of length ($c$) to spread. The governing equations are given by

$$K_m^2 = 2E\gamma_0 = \sigma_c^2Z^2c$$

where $E$ is the Young's modulus and $Z$ the finite width correction factor for the edge-cracked specimen.

Craze growth kinetics in edge-cracked PMMA test pieces immersed in methanol under constant load have been studied by Marshall et al. [4]. They found that the craze initiation and growth characteristics were dependent on the initial applied stress intensity factor $K_0$ ($= \sigma_cZc_0^{1/2}$) and not on the applied stress $\sigma_c$. Two distinct types of craze growth behaviour were observed depending on the magnitude of $K_0$, one type loading to craze arrest and the other to complete fracture. In a more recent treatment [3], Andrews and Levy discovered that in the region where a craze spread at constant velocity, the net section applied stress was the velocity controlling parameter regardless of the presence or absence of a starter crack. Increasing the net section stress would increase the craze tip velocity. The effect of $c_0$ on craze propagation was only a "memory" effect [3]. These findings imply that the $K_0$ dependence of craze velocity is

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not necessarily due to the instantaneous crack tip opening displacement of the starter crack as originally suggested in Marshall et al. [4].

Temperature is a vitally important parameter in solvent-stress crazing [1-3]. For a given environment, Andrews and Bevan [1, 2] have shown that at relatively low temperatures \((T < T_c)\), \(\mathcal{F}_0\) decreases rapidly with increasing temperature up to a characteristic temperature \(T_c\). For \(T \geq T_c\), \(\mathcal{F}_0\) assumes a minimum value \(\mathcal{F}_0^*\) which is temperature independent. Further experimental evidence [5] shows that \(T_c\) is close to the glass transition temperature, \(T_g\), of the swollen material at the crack tip. This temperature dependence behaviour of \(\mathcal{F}_0\) has been shown to conform to a cavitation criterion for craze formation [2, 5].

While attention in all previous work is focused on the initiation and propagation of a craze or crack under essentially constant loads (e.g. Marshall et al. [4]), relatively little is known about the mechanical behaviour of these environment-induced crazes or cracks when subject to other loading conditions such as cyclic loads and monotonic increasing loads (or displacements). The first data on fatigue craze propagation in PMMA immersed in methanol were obtained by Marshall and Williams [8] under a range of loading frequencies. Recently, the present author [9] has also presented some experimental data on the fatigue crack growth rate of PMMA in ethanol and carbon tetrachloride. Benbow [10], on the other hand, investigated the effect of absorption of water on the specific energy for cracking in PMMA under monotonic increasing displacements. He found that the specific work for fracture was approximately four times as much as that in air. However, his cracking experiments were unstable so that cracks were jerky. A parallel experiment as recorded in Fig. 2 shows the results of cracking a 6 mm thick PMMA Outwater testpiece by bending in an Instron testing machine. In air, where cracking was stable, continuous and smooth, the fracture load was approximately constant (AB). However, as soon as carbon tetrachloride was introduced at the crack tip (B), the crack was arrested and the new fracture load considerably increased. This was followed by unstable cracking. These experimental results are in general agreement with those observed by Benbow [10]. It was not readily understood why cracking (under monotonic increasing displacements) was unstable and the specific work of fracture increased. However, Gurney and Hunt [11] suggested that in the presence of a