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Transition from slow to fast crack propagation in PMMA

It is a well-known feature of the fracture behaviour of PMMA that at the critical value of stress intensity factor, K_{IC}, a jump in the crack speed is observed (Fig. 1). Typically for PMMA at room temperature the crack speed jumps from about 0.1 to about 10 to 100 m sec^{-1} depending on testing conditions. Associated with this jump is a significant change in the fracture surface morphology, which can be seen in Fig. 2. The crack propagation direction is from left to right: the slow crack propagation region appears rough and there is an abrupt transition to the smooth high speed region.

Two mechanisms have been suggested to account for this crack speed behaviour. The first, by Williams [1, 2] explains the jump in crack speed as being due to a change-over from isothermal to adiabatic conditions at the tip of a crack in a certain range of crack speeds. Thus, the heat generated by the plastic deformation process at the crack tip builds up in the crack tip region, leading to a rise in temperature and a consequent softening of the material and a reduction in its resistance to fracture.

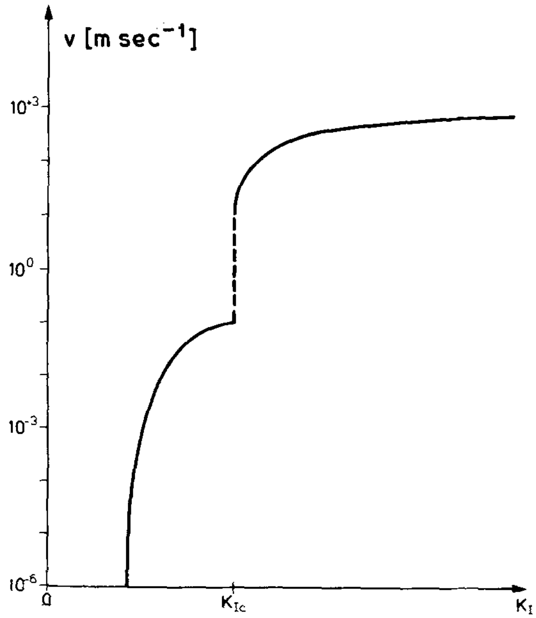

Figure 1 Crack speed v versus stress intensity factor K_I in PMMA (schematic representation).

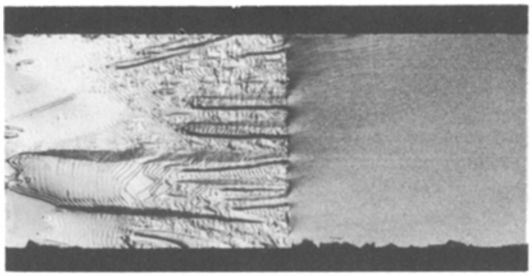

Figure 2 Fracture surface of PMMA $M_w = 8\,000\,000$ showing transition from slow to fast crack propagation. Specimen thickness shown corresponds to 4.16 mm (crack propagation direction from left to right)

In the second mechanism, Johnson and Radon [3, 4] invoked the β-relaxation in PMMA, which is attributed to the relaxation of the ester side groups, to explain the transition in crack speed behaviour. Although no detailed mechanism was put forward coupling the relaxation to crack tip processes the theory was substantiated by the correlation between the temperature dependence of a "time to failure" inferred from fracture experiments and the temperature variation of the reciprocal frequency of the β-relaxation peak.

Support for both these mechanisms is to be found in the literature. One of the present authors [5], for instance, used the model of a moving cylindrical heat source of Weichert and Schönert [6] in the context of an isothermal–adiabatic transition to calculate bounds to the crack speed immediately prior to the transition and found a

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good agreement with experimental values. Broutman and Kobayashi [7] investigated the crack speed transitions in both PMMA and polystyrene at different temperatures and found a correlation with the temperature dependence of the β-relaxation.

The purpose of this note is to report the results of some preliminary investigations on PMMA which, we feel, provide evidence in favour of the isothermal–adiabatic transition mechanism rather than that of the β-relaxation.

We measured the crack speed as a function of stress intensity factor and, in particular, the maximum crack speed, v_t, at the end of the slow propagation region and the critical stress intensity factor K_{IC}, for PMMA of two widely differing molecular weights. Under the β-relaxation model, for material of the same chemical composition and density but different molecular weights, one might expect no differences in these two parameters since the density of the ester groups remains essentially the same. Under the isothermal–adiabatic transition model, on the other hand, one would expect to find differences in K_{IC} and v_t if the volume of plastically deformed material at the crack tip and the resulting heat output varied with the molecular weight. Other work by the authors has shown that the size of the craze zone ahead of the crack tip [8] and the heat generated by a running crack [9] are both markedly dependent on molecular weight in PMMA.

The measurements were performed using a technique developed by Richter [10] in this laboratory. Precracked SEN specimens were subjected to a load which was slowly increased until the crack began to move and was then held constant. The crack length was measured photo-optically by focusing onto the crack plane a line source of light which was parallel to the crack path and at an incident angle of 45° to it. The amount of light transmitted through the uncracked portion of the specimen (i.e. not reflected by the crack surface) was detected with a photo-diode, so that the signal from the diode was inversely proportional to crack length. By feeding this signal to the X-plates of an oscilloscope whilst at the same time modulating the Y-plates with a triangular wave form of known frequency a trace is obtained from which the crack length can be determined as a function of time. A typical example for PMMA of weight average molecular weight $M_w = 8\,000\,000$ is shown in Fig. 3 where the abrupt transition from slow to fast crack propagation can be clearly seen. The modulation frequency here was 100 Hz and the horizontal scale is about one division per millimetre of crack length.

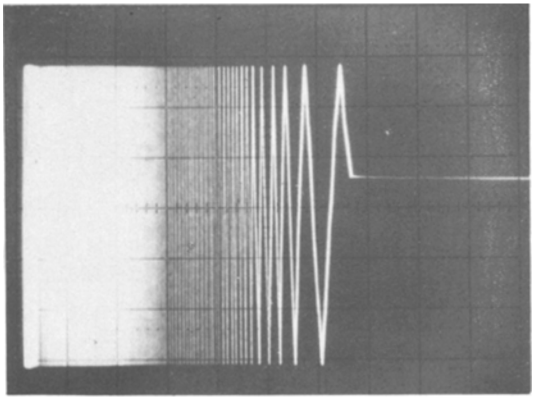

Figure 3 Oscillogram of a time–crack length curve at transition from slow to fast crack propagation in PMMA $M_w = 8\,000\,000$; triangular frequency 100 Hz.

It is perhaps worth emphasizing that this technique allows practically continuous determinations of the crack speed to be made up to the transition point. This is in contrast to the usual method of obtaining the crack speed at the transition which relies on extrapolation.

TABLE I

M_w	K_{IC}(N mm$^{-3/2}$)	v_t(m sec^{-1})
8 000 000	56.1 ± 3.6	0.125 ± 0.051
115 000	38.5 ± 2.0	0.099 ± 0.048

The results of our measurements are summarized in Table I, and for each molecular weight, represent the mean of 24 determinations (the standard deviations are also shown). The second column gives the values of K_{IC}, the stress intensity factor at the transition, and the third the values of v_t, the crack speed at the end of the slow crack propagation region. Although the K_{IC} values are clearly quite different, the scatter bands of the two v_t values overlap. However, on a statistical analysis on the basis of the 48 experiments there is a better than 95% probability that the two values are different. This result thus supports the isothermal–adiabatic transition mechanism for the discontinuity in the crack propagation behaviour in PMMA, rather than that based on the β-relaxation.

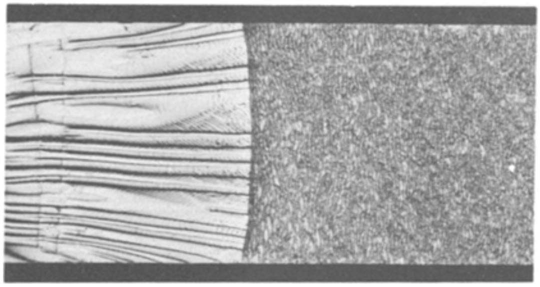

Figure 4 Fracture surface of PMMA $M_w = 115\,000$ showing transition from slow to fast crack propagation. Specimen thickness shown corresponds to 4.75 mm (crack propagation direction from left to right)

By way of comparison, the fracture surface of a specimen with $M_w = 115\,000$ is shown in Fig. 4. Despite the clear difference between low and high molecular weight PMMA (see Fig. 2) in appearance of the fracture surface in the fast propagation region, the fracture surfaces in the slow propagation region appear very similar, thereby suggesting a similar fracture mechanism up to the transition.

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Precision lattice parameters and thermal expansion of paraelectric phase potassium nitrate

Potassium nitrate (KNO_3) exhibits polymorphic transitions. The stable phase at room temperature (II) is of the aragonite type. On heating, phase II transforms into phase I at about 120° C. The structure of phase I, the paraelectric phase, is closely related to the calcite structure and belongs to the space group $R\bar{3}m$. A number of physical properties of various phases of KNO_3 are reported in the literature. Although many investigators have reported the lattice parameters of potassium nitrate, there is a variation of 0.11 Å among the values of the *c* parameter reported by Fischmeister [1] and Chen and Chernow [2] (Table III). Similar remarks hold good in the case of thermal expansion. As the thermal expansion of paraelectric phase is very interesting, in showing large expansion along the trigonal axis and negative expansion in the perpendicular direction, it is thought worth while to determine its precision lattice parameters at various temperatures and to evaluate the coefficients of thermal expansion.

The potassium nitrate powder used in this investigation was prepared from crystals obtained from solution in water of an Analar grade sample. Using a Unicam 19 cm high-temperature camera, powder photographs were taken with Fe*K* radiation from a Raymax-60 X-ray unit in the temperature range 145 to 315° C. With Cu radiation, a considerable overlap of the reflections is observed in the high Bragg angle region. Hence, Fe*K* radiation is preferred. Details of the experimental technique and the method of evaluating the precision lattice parameters and the coefficients of thermal expansion have been described in an earlier paper [3]. Seven reflections $(3\,2\,4)_{\alpha 1}$, $(3\,2\,4)_{\alpha 2}$, $(4\,1\,0)_{\alpha 1}$, $(4\,1\,0)_{\alpha 2}$, $(3\,2\,8)_{\alpha 1}$, $(3\,2\,8)_{\alpha 2}$, and $(4\,1\,6)_{\alpha 1}$ (in terms of hexagonal unit cell)

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