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Physical Properties

Stress analysis of crazes at moving crack tips

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Summary

The finite element method is applied to contours of craze zones in front of moving crack tips in polymethylmethacrylate (PMMA), measured by interferometry, in order to compute the stress distribution. In contrast to the constant stress assumed in the Dugdale model, a stress distribution is found with a maximum at the crack tip then a sharp decrease and a more gradual decline over the larger part of the craze length. Computed stresses as well as the Dugdale stress increase with increasing crack speed and, hence, decreasing loading time. Generally the results obtained are in good agreement with those already found for growing crazes at stationary crack tips.

Introduction

Interference optical microscopy is used extensively to measure the profiles of single crazes at crack tips in various polymers under different loading conditions, as discussed in a review paper (1). The finite element method, which had previously been used to determine stresses in plastic zones (2) and in crazes in thin polystyrene films (3), has recently been applied to optical interference measurements of contours of craze zones in front of stationary crack tips (4). The computed craze stress is not constant, as assumed in the Dugdale model (5), and is found to have its maximum value at the crack tip, then to decrease at first sharply, and then more gradually as the craze tip is approached. However, there is excellent correlation between the average craze stress and the stress derived from the Dugdale model.

In this paper the analysis is extended to crazes at the tips of moving cracks under quasistatic loading.

Experimentation and Computation

Experiments were conducted on small compact tension specimens (Fig. 1) machined from sheets of a commercial grade PMMA (Plexiglas 233 from Röhm GmbH). The methods used to perform the fracture mechanics tests with the application of interference optics, the evaluation technique for determining craze profiles (1), and the short time devices to register moving cracks (6) have been described in the literature.

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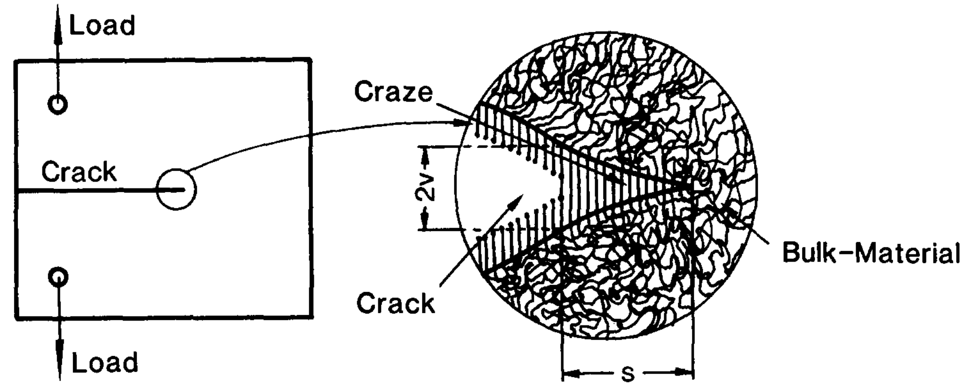

Fig. 1: Schematic diagram of a compact tension specimen with enlargement of the crack tip region.

The finite element idealisation of the crack region in the compact tension specimen is shown in Fig. 2. Due to symmetry, it is necessary to discretise one-half only of the specimen. The interface of the craze and the bulk polymer is modelled as a slit. The craze displacements normal to this surface are prescribed, the time-dependent modulus is specified, and the corresponding craze surface stresses are computed using the approach described previously (4).

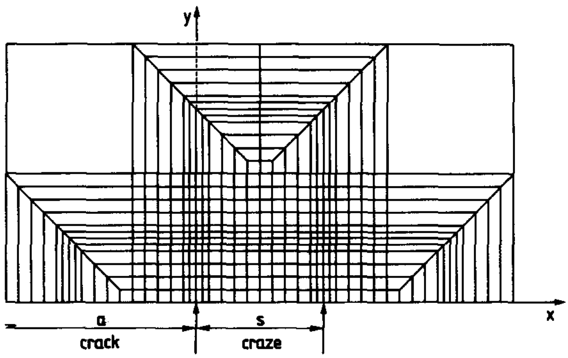

Fig. 2: Finite element idealisation of the crack tip and craze region. By permission of John Wiley and Sons.

Results and Discussion

The previous paper (4) included the analysis of a growing craze in high molecular weight PMMA at the tip of a stationary crack. The stress intensity factor K_I was 0.6 MPa $\cdot$ $m^{1/2}$. If K_I is increased slightly, very slow crack propagation starts and a further increase in K_I increases the crack speed $\dot{a}$ as may be seen from Fig. 3. While K_I changes by a factor of about two the crack speed varies by 10 decades. The craze dimensions, however, change only slightly (1). This may also be visualized

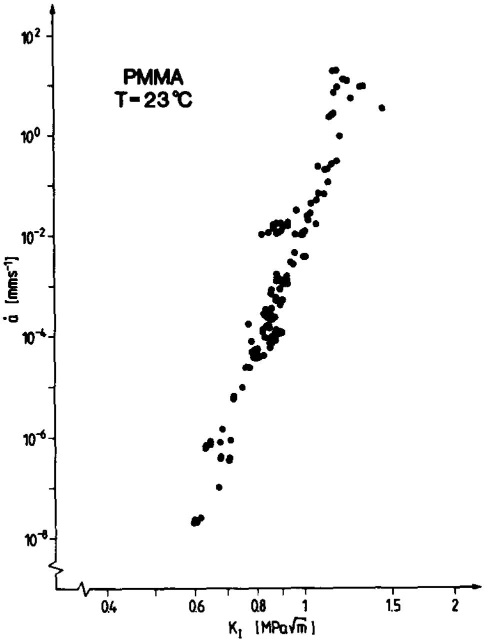

Fig. 3:
Range of continuous crack propagation investigated: crack speed $\dot{a}$ versus stress intensity factor K_I (6). By permission of The Institute of Physics.

from Fig. 4 where the two craze profiles shown are examples exhibiting almost the largest differences in length and thickness. In these cases the maximum craze thickness 2v varies from 2.6 to 3.1 µm while the craze length varies from 32 µm to 39 µm. In Fig. 4 the fits of the Dugdale model to the measured points are also given.

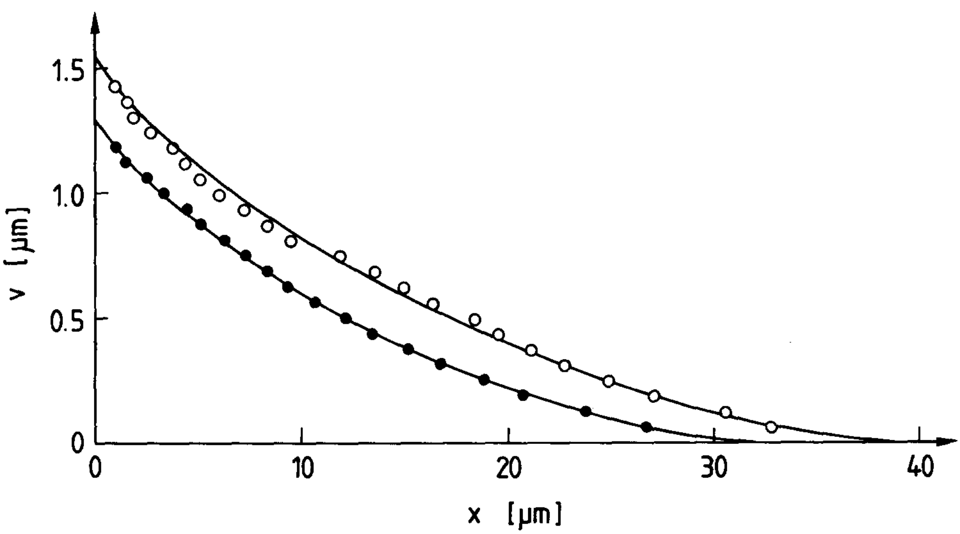

Fig. 4: Craze profiles (upper halves) measured at crack speeds of $2.6 \cdot 10^{-1}$ (o) and $7.1 \cdot 10^{-4}$ (•) mm/s and fits by the Dugdale model (-).

Computed stress distributions along the craze contour are shown in Fig. 5 for four different crack speeds. It should be noted that in accordance with the modified Saint-Venant principle for finite elements (7), computed stress values at distances of less than one element away from the crack tip are neglected. For the four stress distributions the general tendency is that the stress decreases sharply in the region ahead of the crack tip with a gradual decline in stress over the remainder of the craze length. In the craze tip region the computed stresses are almost constant for the particular craze.

As discussed previously (4,8) the accuracy of calculated craze tip stresses is limited because of the difficulty in estimating the precise location of the tip and the exact shape of the displacement profile in this region. However, using a linear extrapolation to the craze tip instead of the Dugdale fit an increase of less than 10 % in craze tip stress normalised to the Dugdale stress is computed.

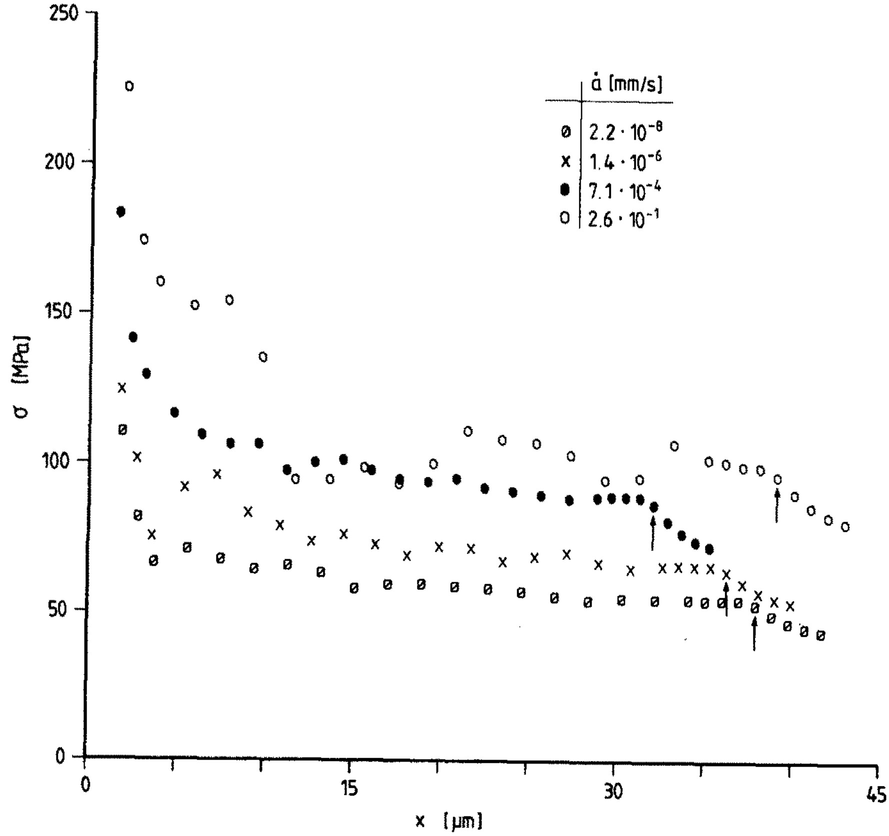

Fig. 5: Craze stress distribution at four different crack speeds ȧ. Craze tips are indicated by arrows.

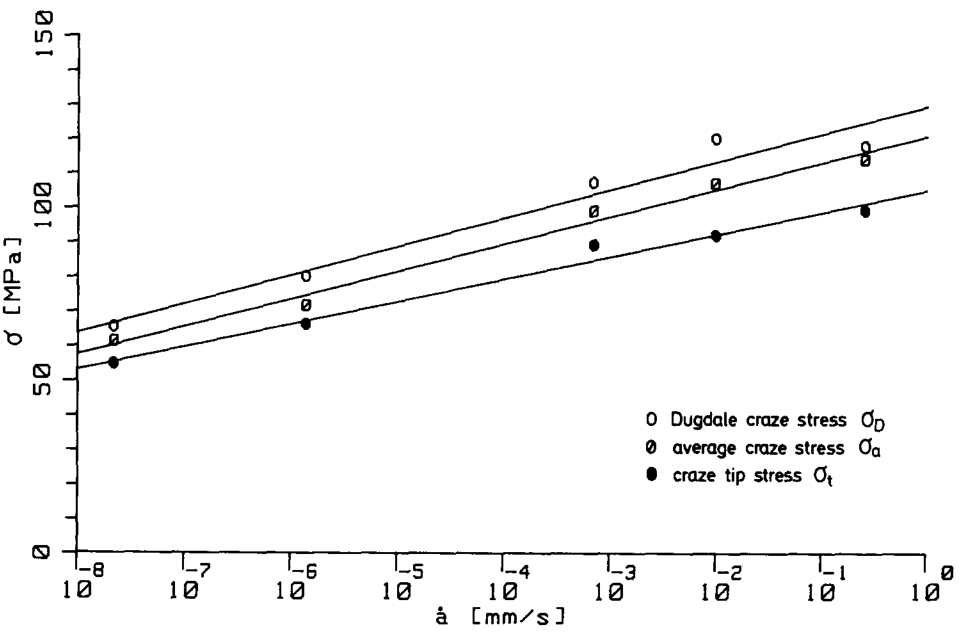

Fig. 6: Rate dependence of craze stress

The stress distribution measured at the highest crack speed shown also exhibits the highest scatter. From the craze profile in Fig. 5 it can be seen that this scatter is due to small deviations only from the Dugdale curve. It should be mentioned that relatively smooth craze profiles have also been observed in this speed range.

From Fig. 5 it also may be deduced that the stress amplitudes increase with crack speed, that is with decreasing loading time. This is shown in more detail in Fig. 6 where the derived Dugdale stress, the computed average craze stress and craze tip stress are plotted as functions of crack speed ȧ. In the speed range investigated these specific stresses increase by a factor of almost two, while the ratio of the stresses remains almost constant.

In general, the results on moving cracks presented here are in agreement with those already published on stationary cracks with respect to the shape of stress profiles and the dependence of the stresses on loading time. Thus, the σ_t results are consistant in a time range from about 10^{-2} s to 10^7s.

Acknowledgements

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