COHESIVE FORCE DISTRIBUTION OF CRACK TIP CRAZES IN FATIGUE OF PMMA

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ABSTRACT

Measurements of crack opening and craze profiles are made under a range of loading histories including cyclical deformations that lead to non-steady crack propagation histories. Of particular interest is the comparison of the distribution of traction transmission of a newly formed craze relative to a cyclically stressed one as it approaches the slow-down phase. Real time, interferometric measurements provide precise and multiple craze profiles during individual cycles. Cyclic deformations reduce the stiffness of craze in its center resulting in a stress drop as part of the craze strength evolution; also, its thickness changes non-uniformly during the acceleration/retardation phases of the advancing craze/crack. The implications are that for quasi-statically formed crazes the craze material can be characterized by a stress-strain relation, while that is no longer readily true for a cyclically deforming crack. Cracks unloaded as part of cyclical deformation histories exhibit crack closure (compression) near the trailing end of the craze.

KEY WORDS

Polymers; fatigue; craze; craze properties; nonsteady crack propagation; cohesive forces; interferometry

INTRODUCTION

Ever since Berry's (1961) early studies the role of crazes in polymer fracture has been investigated as a key element to polymer strength. Gradual improvement in understanding the role and behavior of crazes (Hsiao and Sauer, 1950; Kambour, 1964; Lauterwasser and Kramer, 1979) have made significant contributions to characterizing their role in material behavior in general, and in fracture in particular. Döll and his colleagues, as well as Schirrer (1990) and Hertzberg and Manson (1980) have paid special attention to its "break-down" role in fatigue behavior as summarized in a comprehensive review article (Döll and Könczöl, 1990).

Following leads from fatigue fracture of metals it has become customary to examine fatigue fracture (crack propagation) as if this were a steady state process in the sense that a crack propagates a given length for every cycle. Moreover, there are questions as to whether fatigue crack propagation in polymers is best "correlated" on a "per cycle" basis or relative to the time (frequency) at elevated load. Our own studies (Chang, 1983) with elastomers showed clear preference for the latter (time at load) basis, which was corroborated for structural polymers by

Gregory and Botsis (1991). While this questions may be of secondary value in the evaluation of certain polymers for engineering purposes, the same cannot be said when basic understanding for materials engineering is important. In this context improved comprehension of any potential evolution of time dependent craze behavior, in particular any instability, is required, and this elucidation is the aim of this study.

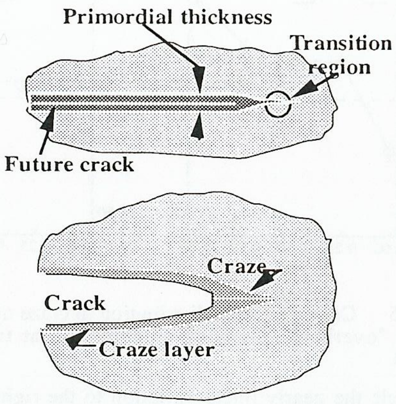


Figure 1: Primordial thickness defined

Motivated by this background the deformation of craze material at the tip of a crack is studied while the whole specimen is subjected to cyclical loading providing mode-I deformations. Interferometric measurements are used to determine the craze profile and crack opening with maximal resolution. These measurements are performed in real time for ten intervals while the crack tip undergoes deformation through a complete load cycle. Resulting displacements are then used to compute associated stresses and reaction-tractions on the craze/crack boundary. In these computations the idea of a primordial craze thickness is important. In the simplest notion this dimension specifies the "gage length" of the deforming craze material so that an extensional strain distribution can be defined along the length of the craze. It will be seen that this concept is only partially successful, namely when the craze is newly formed; however, when the craze has been worked the definition of this thickness becomes less clear.

CRAZE PROFILE MEASUREMENTS

The sequel describes craze profile measurements for several load histories in order to deduce the tractions across the craze. Important in these observations is the concept of the "primordial craze thickness". Crazing is the transformation of continuous and maximal density bulk material into a fibrillated/void-rich material of notably lower density, usually on the order of one half. Thus a strip of bulk thickness h is transformed into a craze thickness of about $2h$. The transformed thickness is called the "primordial thickness"; it represents the unstretched dimension of the craze in the (ideal) stress free state. According to the Lorentz-Lorentz equation the index of refraction is a function of the density, so that the bulk and craze material possess different indices of refraction, which allows total light reflection at the bulk-craze interface for interferometric purposes and thus the determination of the craze thickness.

The Fresh Craze

One sequence of measurements was performed on a craze that resulted from a previous fatigue sequence at 2 Hz ($0.1 < K < 0.35$ MPa $m^{1/2}$) followed by a constant loading at $K = 0.1$ MPa $m^{1/2}$ for ten minutes. By experience, the transient characteristics of the craze material had disappeared during this "rest" period, so that the craze could be considered a "fresh" but not totally unloaded craze. A loading-unloading sequence was then imposed with a maximum of K = 0.3 MPa $m^{1/2}$ and extending over a period of 100 seconds (ν=0.01 Hz), during which four craze profiles were recorded, two during loading and two during unloading. Figure 2a shows a comparison of the measured and computed[1] craze profiles. It is possible to determine in this case a primordial craze thickness. This varies along the craze length, being thinnest at the craze

[1]For computations elastic analysis is employed throughout.

tip and thickest at the crack tip (similar to that in Fig. 4). Consequently, one can also define a strain (stretch) of the craze material along the craze length, which is shown in Fig. 2b.

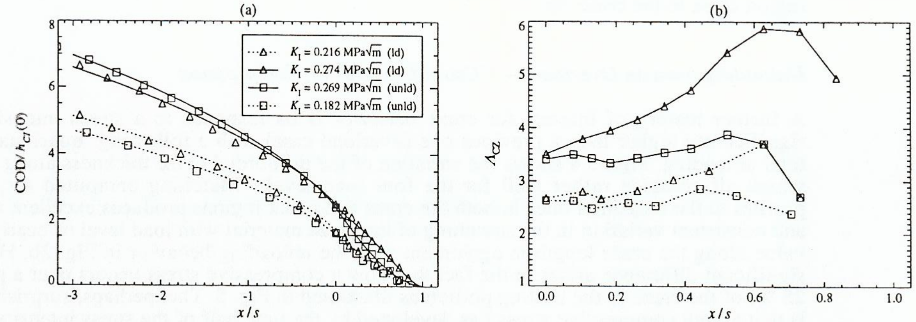
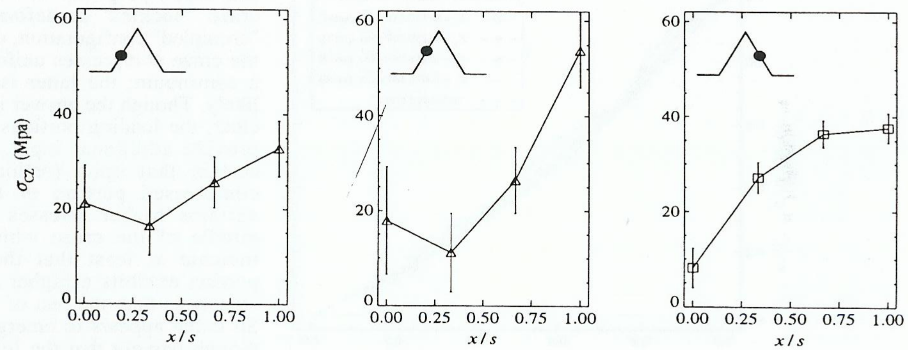


Fig. 2 Measured and computed craze-opening profiles for loading and unloading sequence in quasi-static (slow) deformations. Right Fig.: Fibril stretch along craze.



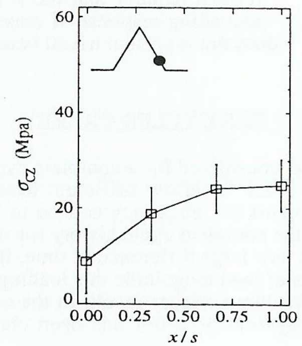


Fig. 3 Cohesive force distribution for loading and unloading sequence in slow deformations.

It is very clear from this figure[2] that the extension ratios in the region close to the craze tip are higher on loading and the beginning of unloading than in the trailing portion, while tending to small values at the craze tip. Moreover, it is clear that although there are history dependent effects operating on the craze material, at the present deformation rate (ν=0.01 Hz) the craze response has a surprisingly large component of recoverable response.

Figure 3 presents the cohesive force distribution for these four cases; further details are presented in (Pulos and Knauss 1996b). It is clear that (a) the maximum stresses occur at the front of the craze where the material has undergone minimum "working" and (b) that the larger

[2]In all figures the craze tip is located at x/s = 1 and the trailing end (crack tip) at x/s = 0

variation in deformation occurs near the middle of the craze but towards the trailing end. One can interpret the behavior at the trailing end of the craze as a region in which the fibrils have been very much stretched such that the molecules are much more oriented there than in the region close to the craze tip.

Unloading from an Overload — "Craze Closure" or Compression

A further history of interest for craze behavior is its response to a stress intensity that is significantly higher than a previous one (overload case) with a following quasi-static (slow) total unloading. Figure 4 shows the variation of the primordial craze thickness along the craze, which all coincide rather well for the four load levels. Matching computed displacement profiles to the measured ones in both the craze and crack regions produces excellent agreement and consistent variation in the stretching of the craze material with load level of nearly constant value along the craze length in agreement with the unloading behavior in Fig. 2b. However, a significant difference arises in the fact that now a compressive stress occurs over a part (20 to 25 %) of the craze in the trailing portion as illustrated in Fig. 5. The, perhaps, surprising feature is that a high compressive stress has developed by the time half of the stress intensity has been reached, which is abated upon further unloading.

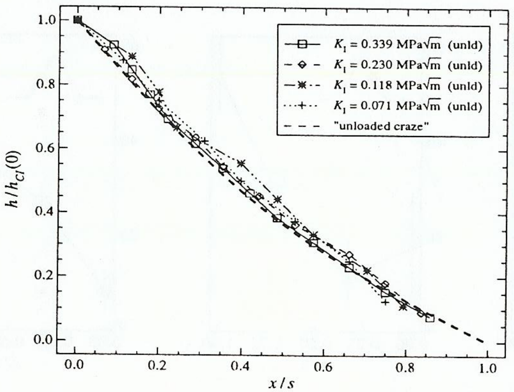


Fig. 4 Primordial thickness for quasi-static unloading case (constant index of refraction).

It is permissible to speculate here for discussion purposes on whether the craze "buckles" or deforms into a "crumpled" configuration, or whether the craze compresses uniformly like a continuum; the latter is not very likely. Though the answer is not very clear, the loading portions of Fig. 3 provide additional input. It seems certain that upon (re)loading the compressed portion of the craze sustains higher stresses than the middle of the craze which would indicate at least that the trailing portion exhibits a higher degree of hysteresis than the rest of the craze. So much appears to emerge clearly, though namely that the loading and unloading response of craze material does not represent trivial behavior.

THE CYCLED CRAZE

Real time measurements of the craze response are next considered for a complete cycle, which is one of a large number applied continuously. In order to allow sufficient time to make eleven measurements bounding ten equal time increments the frequency needed to be held at ν=0.1 Hz. Thus one load increment lasted as long as the complete cycle history for the "quasi-static" test described above. While this may not seem as a large difference in time, it turns out to make a significant difference in the results. In terms of load magnitude this loading falls into the category of "low loads" for which very smooth fracture surfaces result. In the companion presentation (Pulos, 1996a) this type of crack propagation behavior has been classified as "coherent."

The most distinctive feature is illustrated in Fig. 6 where the primordial craze thickness is shown at each step. While the idea of the primordial thickness is to represent an (invariable) craze configuration the data indicates a quantity that varies throughout a cycle: At the peak of

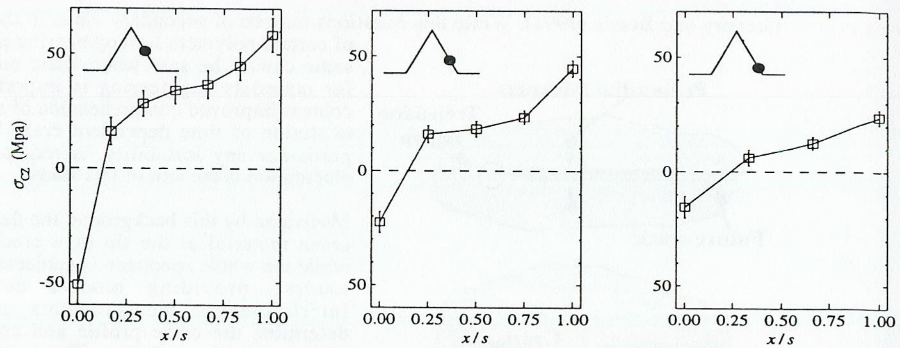
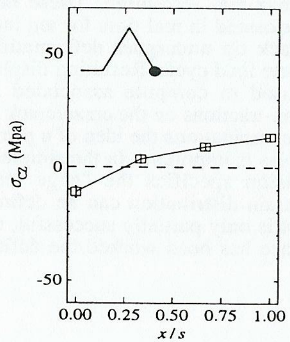



Fig. 5 Cohesive force distribution in craze upon unloading from "overload", showing compression at trailing end of craze.

the cycle the nearly linear variation to the right in the figure results, while for lower portions of the load cycle the curves to the left are more appropriate[3]. Clearly, the traces for different increments vary too consistently to be attributable to statistical error. An immediate consequence of this result is that a stretch ratio for the craze material cannot be defined uniquely and a "stress-strain" behavior for the craze cannot thus be determined with confidence, either.

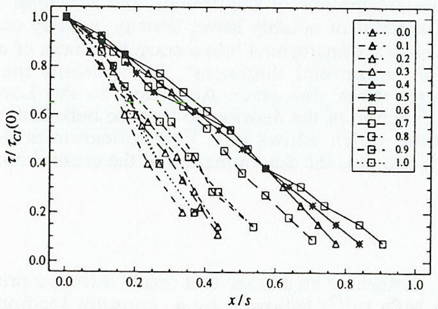


Fig. 6 Primordial thickness at each measurement interval during a cycle (constant index of refraction).

One possible source of this behavior may be associated with the optical properties of the craze. We have had to assume that the craze properties are invariant in the thickness direction so that the only reflection for interferometric purposes occurs at the bulk-craze boundary. On the other hand, if during part of a cycle the craze fibrils are "buckled" or "crumpled" a secondary structure of different density may form along the length of the craze as a result of the compaction at the low part of the cycle. This possibility has been explored, but space in this presentation is insufficient to delineate details. The seemingly best choice resulted from accepting a primordial thickness represented by one half of the linear distribution in Fig. 6 (maximal cycle load amplitude) and subsequent evaluations are based on that choice.

[3]There are vestiges of this spread of the primordial thickness variation in the data for the quasi-static loading-unloading case represented in Fig. 2 and 3, though that data is very much closer to that in Fig. 4 than for the present case.

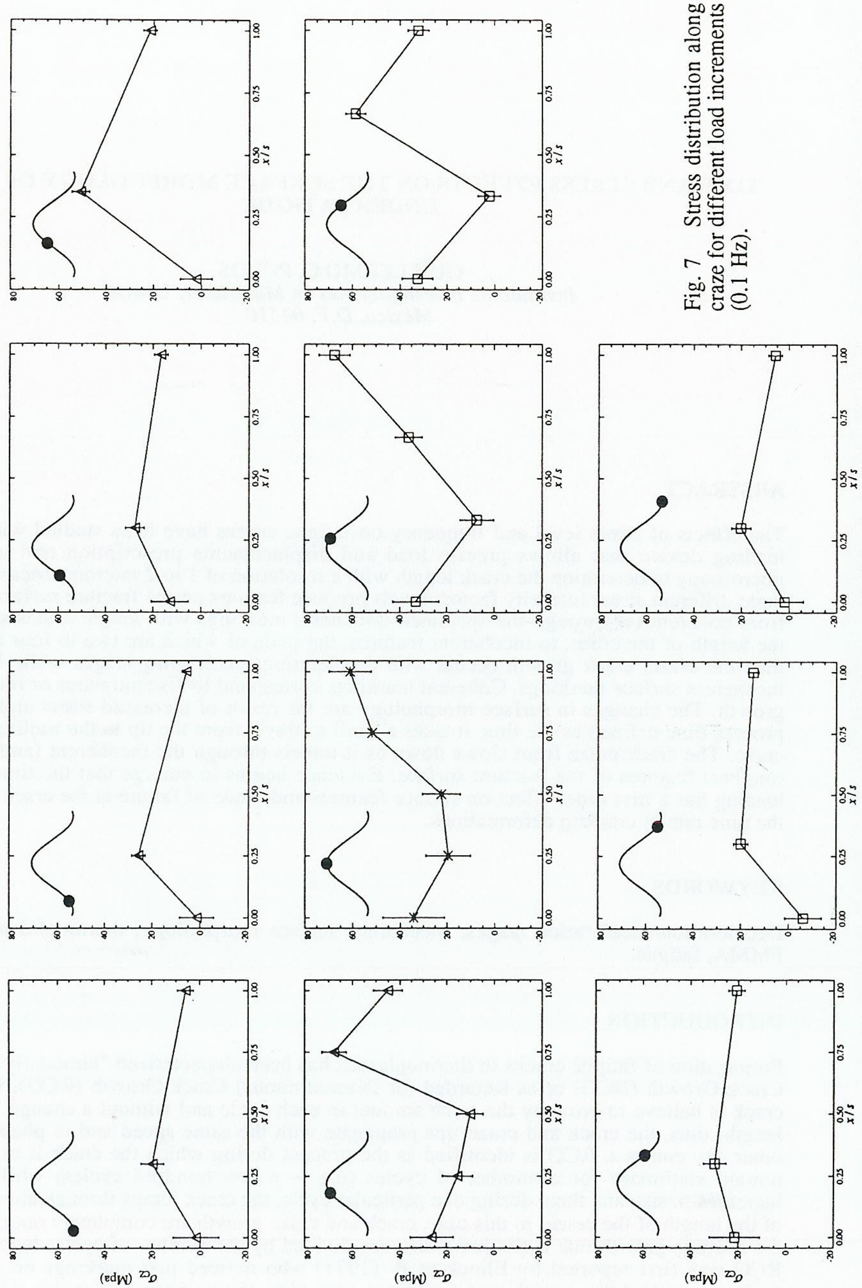


Fig. 7 Stress distribution along craze for different load increments (0.1 Hz).

Figure 7 presents the cohesive force distribution for the cycled craze. It should again be born in mind that the difference between the previous (slow) histories and the present cyclic loading/unloading situation results from a change in the cycle frequency by a factor of ten only. For reference purposes it needs to be pointed out that the bulk material incurs a change in modulus (stiffness) of only 10% in a decade of time, hardly commensurate with the drastic difference observed here.

CONCLUDING REMARKS

The response of craze material under three significantly different load histories has been studied through the use of interferometry for measuring the craze-bulk interface deformations. While there is insufficient space to illustrate consequential results, it is worth noting that relations between the cohesive forces and the displacement of the bulk-craze interface can be estimated. This result is reasonably similar for the cases considered here and shows that the highest tractions typically occur near the tip of the craze, falling off towards its trailing end; the corollary result of the craze stiffness variation shows that in terms of a force craze-opening-displacement relation the cohesive forces follow a strictly softening characteristic.

REFERENCES

Berry, J. P. (1961). Fracture Processes in Polymeric Material. 1. The Surface Energy of Poly(methylmethacrylate). *J. of Pol. Sci.*, **50**, 107-115.

Chang, S. K. Y. (1983). *Crack Propagation in Viscoelastic Materials under Transient Loading with Application to Adhesively Bonded Structures*, Engineer's Thesis, California Institute of Technology.

Döll, W. and L. Könczöl (1990). Micromechanics of Fracture under Static and Fatigue Loading: Optical Interferometry of Crack Tip Craze Zones. In: *Advances in Polymer Science: Crazing in Polymers* (H.H. Kausch, ed.), Vol. 91/92, pp. 137-214. Springer-Verlag, Berlin.

Gregory, B. L. and J. Botsis (1991). Experimental Investigation of the Effects of Stress Rate and Stress Level on Fracture in Polystyrene. *J Mat Sci*, **26**, 1015-1026.

Hertzberg, R. W. and J. A. Manson (1980). *Fatigue of Engineering Plastics.* Academic Press, New York.

Hsiao, C. C. and J. A. Sauer (1950). On Crazing of Linear High Polymers. *J App Phys*, **21**, 1071-1083.

Kambour, R. P. (1964). Structure and Properties of Crazes in Polycarbonate and Other Glassy Polymers. *Polymer*, **5**, 143-155.

Lauterwasser, B. D. and E. J. Kramer (1979). Microscopic Mechanisms and Mechanics of Craze Growth and Fracture. *Phil. Mag. A*, **39**, 469-495.

Pulos, G. C. (1996a). Time and stress effects on the surface morphology of PMMA under fatigue. In: *9th International Conference on Fracture*, Sidney.

Pulos, G. C. and W. G. Knauss (1996b). Nonsteady Crack and Craze Behavior in PMMA under Cyclical Loading: III. Report SM 96-11, California Institute of Technology, City.

Schirrer, R. (1990). Optical Interferometry: Running Crack-Tip Morphologies and Craze Material Properties. In: *Advances in Polymer Science: Crazing in Polymers* (H.H. Kausch, ed.), Vol. 91/92, pp. 215-261. Springer-Verlag, Berlin.