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On a fatigue crack-front marking technique for polymers

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A fatigue crack-front marking technique using small tensile overloads is described. In this technique, two small overloads are chosen to produce distinct striation spacings which can be used to encode a binary marker on the fatigue fracture surface. Post-mortem detection of these binary coded markers then enables a direct correlation with the load history. This technique is particularly useful for the study of early crack development or crack initiation in smooth bar samples. Periodic insertion of binary coded markers during the entire testing period could allow a precise determination of the crack initiation time. The study of fatigue fracture mode transitions is also facilitated with this crack-front marking technique.

1. Introduction

The task of re-creating and understanding the fatigue crack growth process in a specimen is greatly simplified when fatigue striations can be found. The striations mark the instantaneous position of the crack front, hence allowing post-mortem analysis of crack front shapes, crack growth rates and crack growth transitions. When a complete striation history is recorded (or when it is known between two specified times and locations) a direct correlation with the applied load history and with external crack growth measurements would allow quantitative specification of crack initation times and crack growth rates. Unfortunately, the polymer fatigue process is replete with surprises. Mode transitions (for example, from a plane strain to a plane stress mode or from a multiple load cycle to a single load cycle crack advance mechanism) create ambiguities in attempts to interpret fracture surface structure in terms of load cycle histories. The difficulties are particularly pronounced for unnotched polymer specimens, where visual monitoring of interior cracks (crack shapes and lengths) are seldom possible and where discontinuous crack growth (multiple load cycles per crack arrest band) is often observed. Under these adverse conditions, it becomes nearly impossible to ascertain crack initiation times and quantitatively to decipher crack growth histories from the fracture surface features. Undeniably, there is a need for an experimental technique that would "mark" the fatigue crack front at known times (or time intervals). This marking technique would be required to produce a clearly recognizable imprint, yet be sufficiently innocuous so as not to alter the crack growth process.

Singian *et al.* [1] have reported a method of marking the fracture front by evaporating various metals into the crack and by using X-ray microanalysis in a scanning electron microscope for detection of the crack front. This technique is particularly useful for situations where the crack front is highly curved or irregular, or when striations do not appear. The long interruption times required for evaporation and the limited number of marking layers that can be evaporated (each layer adds to the thickness of the previous layer, thereby making detection of the covered layer more difficult and possibly obscuring surface detail), however, impose limitations on this evaporation technique.

This paper will describe an alternative marking technique which is based on inserting small overloads to produce perturbations on the fracture surface. If these perturbations can be inserted in

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a specified coded sequence, then subsequent decoding of the striation pattern should give a precise striation history. The simplest, yet perhaps most elegant approach would be to choose two distinct overload levels which can be used to represent the elements (0 and 1) of a binary code. Sequenced binary coded markers can then be introduced at desired intervals for permanent surface crack markings for use in future analysis. The usefulness of this technique is limited to overloads that leave minor, yet perceptible, perturbations on the fatigue striation surface features. If the overloads are too severe, adverse effects may result, as shown, for example, by Banasiak *et al.* [2], who observed significant crack retardation with large tensile overloads in polycarbonate and by Pitoniak, *et al.* [3], who reported similar retardation in polymethylmethacrylate.

2. Experimental methods

Large tensile bars of cross-section 1.3 cm x 0.32 cm and gauge-length 5 cm were machined from 0.32 cm thick extruded polycarbonate sheet and from compression moulded polycarbonate. Samples were sanded with various grades of silicone carbide paper and polished with AlO_2 powder (down to 0.05 μm powder). All fatigue tests were performed in tension on an Instron Model 1350 servohydraulic testing machine with an R value (mininum to maximum load ratio) of 0.05 and a peak to peak stress amplitude of 34 MPa. Fatigue tests were run under sinusoidal loading at 1 Hz (with lifetimes of approximately 7000 cycles) for the compression moulded samples and at 5 Hz (with lifetimes of approximately 50 000) for the extruded sheet specimens.

3. Binary coded overload marking technique

At selected intervals, binary coded overload cycles were inserted for crack front markings. For the binary coding, two different overloads were applied, with the overloads corresponding to the binary digits, 0 and 1. Just before insertion of the coded markers, the fatigue load cycling was interrupted at the minimum applied tensile stress level. The first binary marker overload (0 or 1) was selected by adjusting the load amplitude dial of the servohydraulic testing machine and a single load cycle was applied. This process was then repeated with the appropriate overloads until the desired binary code pattern was inserted. A sequence of four overloads took roughly 30 sec to complete. The fatigue cycling was then immediately resumed at the test frequency. The crack front marking overloads were chosen to be relatively small to ensure that the nature of the fatigue crack propagation process remained unaltered. This was verified by comparing the fatigue behaviour of both marked (encoded) and unmarked samples, where the comparisons revealed no basic difference in behaviour.

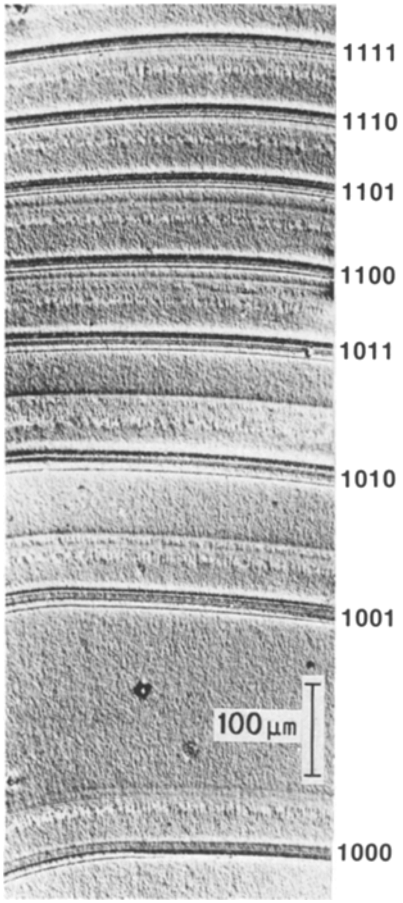

Figure 1 An optical micrograph of the fatigue fracture surface showing the 8 binary coded marking patterns listed in Table I. Fatigue striations can be seen between markers.

Fig. 1 shows a portion of the fatigue fracture surface of a compression moulded sample which illustrates a series of binary coded markers. Table I lists the coded patterns that were inserted. A binary 0 corresponded to an 8% increase in the stress amplitude while a binary 1 corresponded to a 12% increase. In both cases, the minimum stress level was kept constant while the maximum level

TABLE I The binary coded marking patterns that were inserted in the portion of the fatigue history for the sample shown in Fig. 1. The normal fatigue amplitude (peak to peak) was 34 MPa. The cycle number represents the load cycle for the first overload of the corresponding marker and the cycle interval, the number of fatigue cycles between the previous and present markers.

Binary coded marker	Cycle number	Cycle interval
1000	17565	
1001	17700	131
1010	17778	74
1011	17850	68
1100	17900	46
1101	17953	49
1110	18000	43
1111	18050	46

was adjusted to produce the desired overloads. The binary markers exhibit certain characteristics which must be understood for proper decoding. In all 8 markers shown, the leading binary 1 overload is clearly distinguishable with a sizeable spacing, whereas subsequent binary 1 overloads, although also plainly evident, have smaller spacings. This is particularly clear in the 1111, 1110 and 1100 markers, where the binary 1 overloads are encoded in succession. A possible mechanism for this enhanced spacing of the initial overload may have been suggested by Jacobi [4], who observed that insertion of a no-load "rest" period during fatigue cycling led to an initially higher propagation rate upon resuming the fatigue cycling (see Fig. 20c of [4]). Before the insertion of the initial binary 1 overload, the load cycling is halted to allow dialling of the new setting for the overload amplitude. This short "rest" period may account for the enhanced spacing of the initial overload. Subsequent binary 1 overloads do not require resetting of the amplitude dial, hence no additional rest periods (or much shorter ones) are required.

The binary 0 overloads in Fig. 1 require more careful consideration. They show up readily when they are surrounded by binary 1 overloads (to yield a 101 pattern) as seen in the 1010, 1011 and 1101 binary patterns. The surface appearance of the binary 0 overload is pronounced by the highly visible binary 1 overloads. However, when binary 0 overloads are placed in succession, the individual overloads are often not as readily distinguishable, as can be seen in the 1000, 1001 and 1100 markers. This loss of resolution places a lower limit on the size of the overloads that can be chosen for the marking technique.

Many other overload levels were tested for use in the binary markers, with the same basic conclusions for encoding and decoding having been found to apply. Improved resolution was obtained with larger overloads, but at the expense of creating greater disturbances. Fig. 2 shows a binary coded marker (10011) with 10 and 20% stress amplitude overloads used for the binary 0 and 1 overloads, respectively. The marker is clearly defined, especially with the large spacings of the binary 1 overloads. The final two binary 1 overloads created spacings significantly smaller than the initial binary 1 overload (although considerably larger than the intervening binary 0 overloads). As stated earlier, the no-load "rest" period mechanism may produce an enhanced spacing for the initial overload. The spacing of the latter two binary 1 overloads may be further decreased due to crack retardation induced by the initial overload. Several possible retardation mechanisms may apply: crack closure, with residual compressive stresses which hold the crack faces together; crack blunting, with a reduced stress intensity factor at the crack tip; or residual compressive stresses ahead of the crack tip, which lowers the effective tensile stress in the plastic zone [2]. All these mechanisms could lead to retardation of crack growth, hence shorter spacings in the subsequent overload cycles.

4. An application of the crack-front marking technique

The binary coded overload marking technique has been used to clarify the nature of the fatigue crack growth in polycarbonate [5]. In unnotched polycarbonate specimens, a part-through surface crack will often undergo a transition from a plane strain crack growth normal to the loading direction to a shear fracture mode at 45° to the loading direction. This transition is illustrated in Fig. 3, which is an optical micrograph of a thinned section (approximately 50 μm thick), whose plane contains the loading direction and the crack growth direction. The 45° shear growth is clearly evident under transmitted light using crossed polaroids. At the beginning of the transition, the shear fracture propagates in two separate cracks (at ± 45° to the normal) which are not connected to the main crack. Eventually, the main crack merges with one of the two partial shear cracks. In Fig. 3, the main crack has merged with the upper of the two shear cracks.

The scanning electron micrograph of Fig. 4

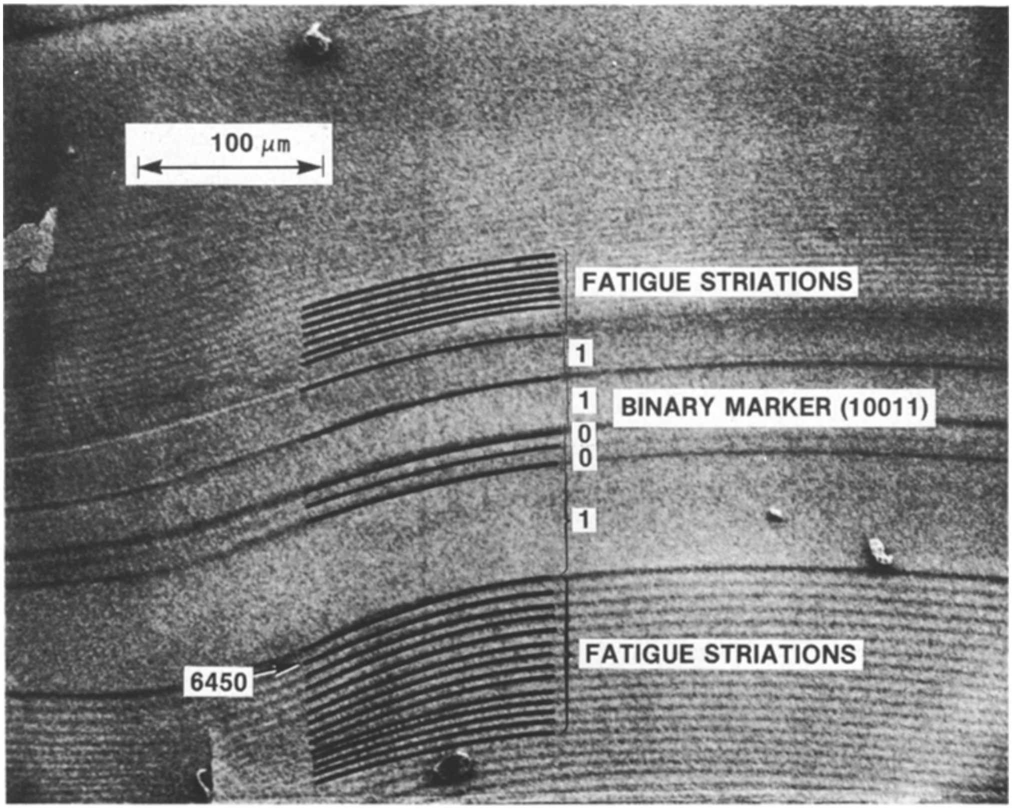

Figure 2 A scanning electron micrograph showing a binary marker (10011) with fatigue striations on either side. The initial binary 1 overload has an enhanced spacing compared to the final two binary 1 overloads.

shows a surface view of such a transition. This micrograph is taken from the same sample shown in Fig. 2, hence the binary 0 and 1 overloads were 10% and 20%, respectively. Striations can be seen in both regions, i.e., in the plane strain and in the shear failure zones. The striations in the plane strain zone are the familiar fatigue striations which develop on each cycle of loading. Although not directly evident in Figs 2 or 4, the single cycle nature of this crack propagation mode was verified by the binary marker technique. The striations in the shear fracture region are more closely spaced than the plane strain striations and they show considerable evidence of ductile flow, which reflects the extensive shear deformation that has occurred in the sheared zones.

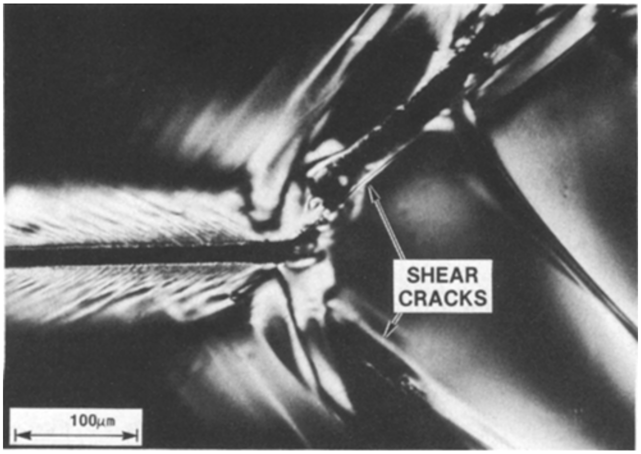

Figure 3 An optical micrograph of a thinned section containing a crack during the plane strain to shear fatigue fracture mode transition. The plane of the section contains the crack growth and the loading directions. Two disjoint shear cracks grew at ± 45° to the main crack until the ligament between the main crack and the upper of the two shear cracks tore. At that point, the bottom shear crack stopped growing.

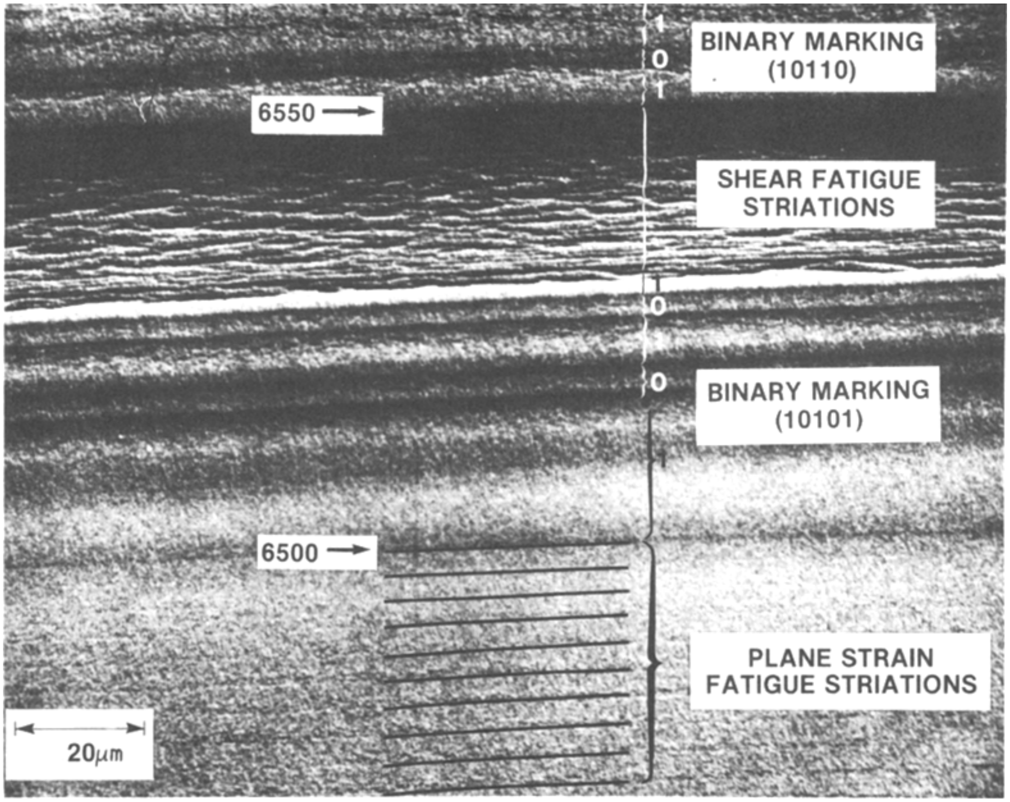

Figure 4 A scanning electron micrograph showing fatigue striations in the plane strain region and in the shear fracture region at a mode transition. Two binary markers can be seen (10101 and the beginning of 10110).

The binary markers shown in Fig. 4 are relatively large, causing the crack front to advance as far during the five marker overload cycles as it does for the 45 load cycles between the markers. The nature of the fatigue crack advance mechanism, however, has not been qualitatively affected. Fig. 5 shows an enlargement of the 45 fatigue striations between two other markers in the shear zone. A careful examination reveals approximately 45 striations, hence indicating that the shear fatigue fracture also proceeds in a single cycle crack advance manner. The apparent uniformity of the shear striations and the close correlation in the number of striations observed with the number of applied load cycles indicate that the overloads were sufficiently small that significant crack retardation or arrest did not occur.

5. Discussion

Perhaps the greatest use of the binary coded marking technique would be for the study of early crack development in smooth bar samples. Knowledge of crack initiation times is highly desirable, but seldom available, since early crack growth is difficult to detect and often impossible to observe in opaque specimens. Binary coding would allow periodic insertions of unique (distinguishable) compact markers without the need to establish when and where the crack initiated while the testing was in progress. At the end of the test, the markers could be used to trace the crack development. This technique, of course, is applicable only when striations are formed by the cyclic loading. However, if striations are only formed during portions of the fatigue process, the binary coded markers would specify exactly when the striations were created.

The binary coded crack-front marking technique requires judicious application for optimum encoding and decoding on the fracture surface. The time-dependent relaxation response of polymers, the crack blunting and residual stresses created by the advancing crack and the time delays required for overload insertions all can conspire to produce variations in the spacings of overload striations. A careful understanding of

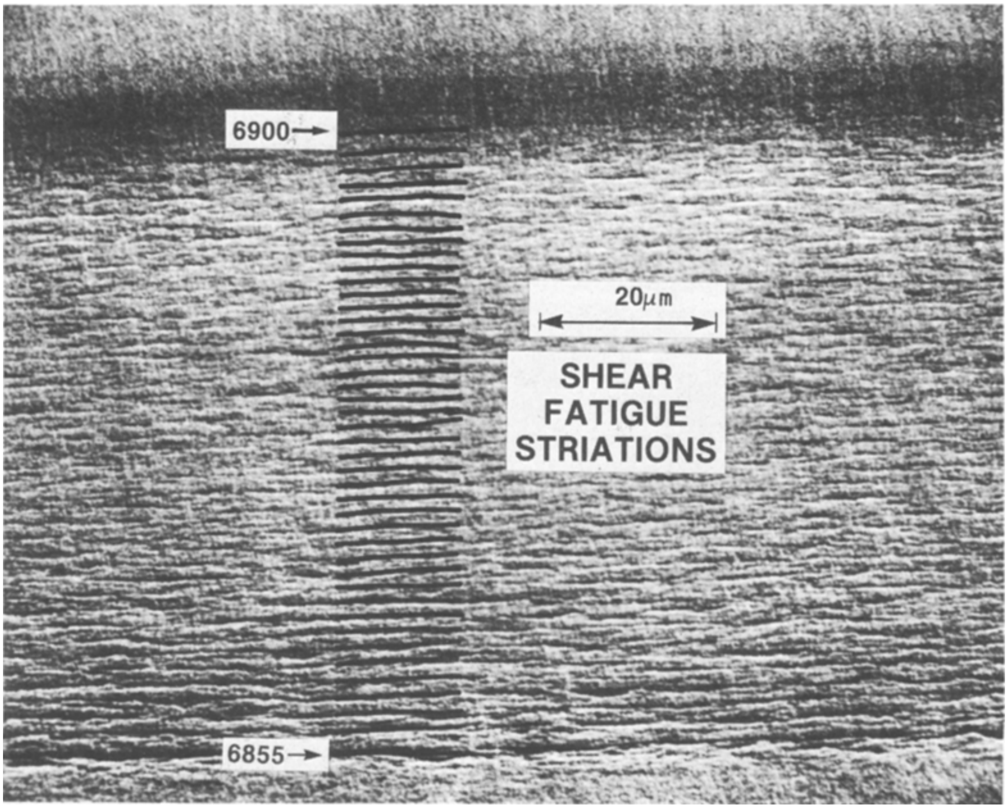

Figure 5 A scanning electron micrograph showing the shear fatigue striations between the markers. 45 load cycles occurred between the markers, which is roughly the number of shear striations that can be counted, hence indicating single cycle crack advance, and little or no crack retardation.

the material response is thus necessary for proper selection of the overload amplitudes and interpretation of the resultant surface markings.

The time-dependent viscoelastic response of polymeric materials suggests that variations in load cyclic frequency or simply variable rest periods may be sufficient to leave perturbations on the striation structure without having to resort to overloads. On the other hand, these techniques may be used in addition to overloads to enhance the resultant surface markings.

Acknowledgement

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