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Non-steady, periodic behavior in the dynamic fracture of PMMA

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Abstract. A crack moving dynamically through a sheet of Polymethylmethacrylate at high average velocity is found in reality to propagate in a non-steady, periodic, and perhaps discontinuous fashion. The spatial period of the fracture process in the direction of travel, or banding morphology, is of millimeter size and is consistent both in magnitude and discontinuous nature with a crazing mechanism proposed in fatigue settings. The band size in both the dynamic and fatigue environments scales with the applied stress intensity. This commonality has importance in modeling. It suggests that a single mechanism is fundamental in both dynamic and fatigue loading regimes.

1. Introduction

A crack dynamically propagating through an elastic solid is typically modeled as being steady [1]. This supposition is based on the assumption that the material separation arises from a process that can be treated as continuous. An accompanying inference is that the fracture velocity is governed by the state of stress encompassing the crack. In a two dimensional setting this notion is embodied in the relationship between the dynamic stress intensity factor and crack velocity. Experiments designed to correlate with the theoretical assumptions frequently employ amorphous materials to avoid introducing macroscopic length scales such as grain boundaries. Indeed, experiments using photoelasticity conclude that as the spatially averaged deformation surrounding a dynamically moving crack is increased, its propagation velocity is augmented [2, 3]. However, when other methods of measurement are employed that are spatially more precise (e.g. caustics), the kinship between the instantaneous intensity of deformation and the crack velocity appears tenuous [4]. There are other difficulties with the elastodynamic idealization. In particular cracks tend to propagate at much less than the elastic wave speeds of the material [5].

Various explanations have been proposed to account for these discrepancies between observation and theory. The experiments have been questioned for not properly including transients [6, 7], measurement delays [8], and three dimensional effects [9]. Likewise, crack propagation models have been improved to partially incorporate observed microstructural behavior at the crack tip. These microstructural processes such as micro-fracturing, void growth and coalescence are hypothesized to be fundamental to fracture [10], and may explain oscillations in the measured stress intensity [11] and intrinsically slow crack speeds [12].

Unfortunately, the task of including microstructural effects and predicting the ensuing fracture morphology is made arduous by their apparent haphazard disposition and inherent geometrical complexity. Typically, the fracture morphology is the most concrete discernible evidence of microstructural events. Hence the fracture surfaces of many materials have been studied extensively [13] and have been categorized in terms of material properties [14], fracture velocity [15, 16], and local stress intensity [4].

Here a full field optical technique is employed to capture the out-of-plane displacement surrounding a crack rapidly propagating though a thin sheet of Polymethylmethacrylate (PMMA). The data clearly displays intrinsic non-steady and periodic fracture behavior in this amorphous thermoplastic. This non-steady behavior is accompanied by a particularly simple periodic fracture morphology. The fracture surface consists of periodic bands in the direction of crack propagation that span the thickness of the sheet. The width of the bands scales roughly with the local stress intensity at the crack. This band size dependence on the stress intensity is not only true in the dynamic cases reported here but in fatigue tests as well.

2. Description of the experiment

The goal of the experiment is briefly, to approximate an infinite plate impulsively loaded along the crack flanks with a uniform pressure [17]. This work complements previous dynamic caustic experiments [4, 18] with refinements allowing interferometric measurements.

Specimens were constructed from pellets of PMMA that were cast, and annealed into smooth flat sheets nominally 300 mm square by 4.5 mm thick. The mold used to cast the Acrylic was polished with 0.5 μm diamond grit. These sheets were notched using a straight end mill and a file. A starter crack was initiated using an impulsively loaded razor blade wedged in the filed notch. The anterior surface was vacuum coated with pure aluminum to give a specularly reflective surface. To provide a testing time free of reflected waves from the boundaries of approximately 150 μs, additional cast sheets of PMMA were glued to the aluminum coated material using Methylene Chloride. This specimen geometry is shown in Fig. 1.

The crack flanks were impulsively loaded by discharging a high voltage capacitor bank through a copper strip by means of a mercury switch. This strip was wrapped three times to improve the load characteristics for a given current over a single wrap design [19]. A schematic of this loading coil is shown in Fig. 2, with a typical loading pulse shown in Fig. 3. The width of

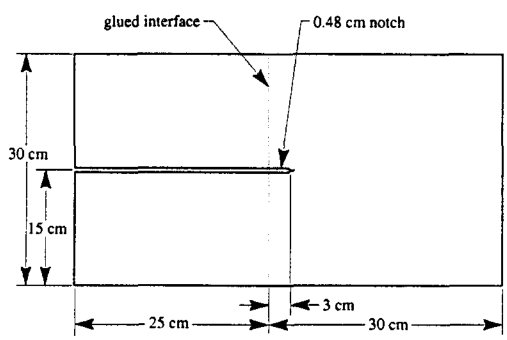

Fig. 1. PMMA dynamic specimen geometry.

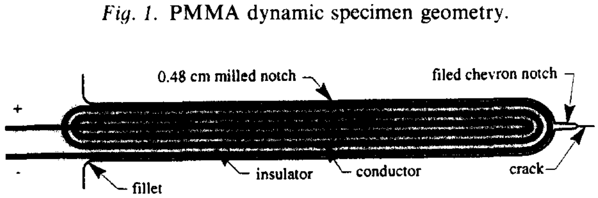

Fig. 2. Schematic of the electromagnetic loading coil, 5 mm wide × 0.5 mm thick copper, 25 mm wide × 0.2 mm thick cellophane insulation.

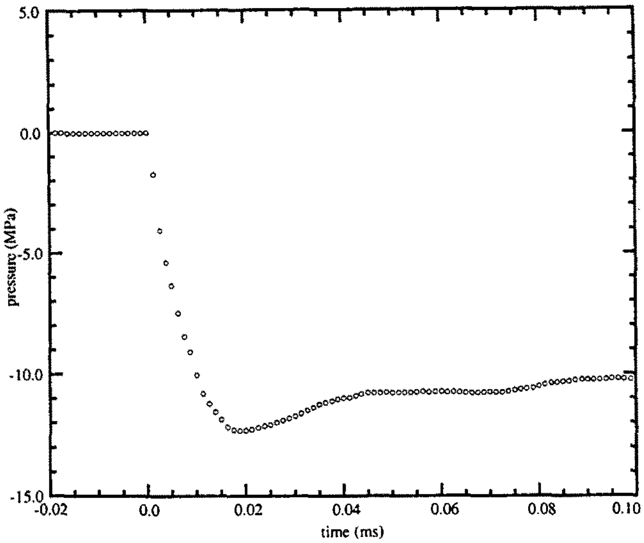

Fig. 3. Typical loading pulse along the crack flanks.

the milled notch was set to allow a snug fit of the loading coil between the crack flanks without pre-loading the crack.

The out-of-plane displacement of the reflective surface was measured using a Twyman-Green interferometer [19] and a high-speed rotating mirror camera. The light source was a Spectra-Physics model 166, 5 W Argon Ion laser tuned to 514 nm with 15 ns light pulses generated from a Bragg cell. The laser light was expanded, filtered and collimated to 50 mm in diameter through a 30X microscope objective, a 12.5 μm diameter pin hole, and a Nikon 200 mm f/4 IF lens. The collection optics include a Nikon 200 mm f/2 IF lens, a 40 mm field lens at the intermediate focal plane, and a Nikon TC-14B teleconverter and a Nikon 200 mm IF lens between the intermediate focal plane and the final image. The film used was Kodak T-Max 400 processed with Kodak T-Max developer. A schematic of this apparatus is shown in Fig. 4.

The finished specimen with the loading coil inserted, was placed in an insulated enclosure that had several small apertures to allow passage of the light from the interferometer and the current from the capacitor bank. This enclosure protects the surround instrumentation by containing debris from the specimen and loading coil. The specimen was aligned so that the normal to the anterior surface just in front of the crack tip was parallel with the laser. The optics were focused

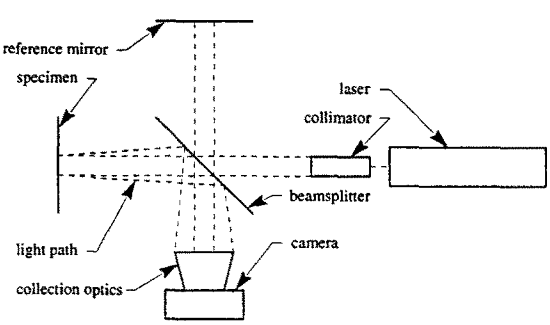

Fig. 4. Schematic of the Twymann-Green interferometer to measure out-of-plane displacement [19].

on this reflective surface. Photographs were taken every 20 μs starting at 100 μs before the start of the loading [20].

3. Experimental results

A typical enlargement of a photograph from this interferometer experiment, at 40 μs from the start of the loading is shown in Fig. 5. Based on the data at 20 μs and 60 μs the crack is moving at an average velocity of 0.5 mm/μs. The interferogram has three superimposed displacements. First there is the initial shape of the specimen, and second, the deformation due to the Poisson contraction of the material from the mode-I loading of the crack. Both of these deformations are smooth [20]. The third deformation is a ripple pattern radiating out from near the crack tip.

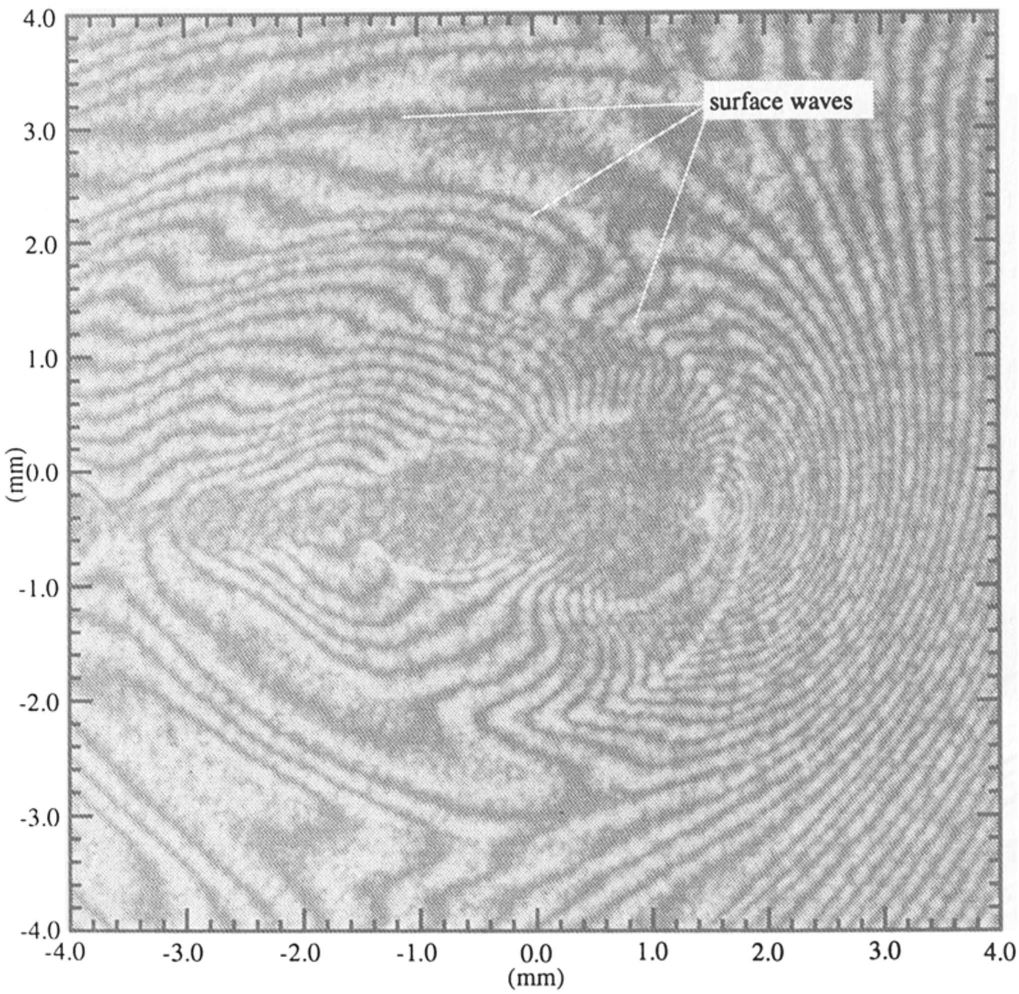

Fig. 5. An interferogram of the out-of-plane surface displacement of a crack moving at an average velocity of 0.5 mm/μs in a 4.59 mm thick plate of 100 M Polymethylmethacrylate (PMMA). Contours represent a 257 nm change in elevation. Surface ripples are propagating at approximately 1 mm/μs.

The dark region near the crack tip is a shadow spot attributed to angular aperture limitations of the collection optics.

The ripple pattern is Doppler shifted from the crack tip by distances consistent with a crack speed of 0.5 mm/μs and a surface wave speed of 1 mm/μs. This surface wave speed is approximately the elastic shear or Rayleigh wave speed of this material.

At the location of the crack in Fig. 5, the surface morphology is shown in Fig. 6. This photograph was taken using a microscope with reflective illumination at 45° to the surface normal. Figure 6 shows both the top and bottom halves of the fracture surface. The halves were aligned in the crack propagation direction at the tip of the starter crack.

As shown in Fig. 5, a crack is propagating through an amorphous material, PMMA, at about one-half of the shear wave velocity. At this speed, waves are radiated away from the moving crack tip with approximately the shear wave velocity. These surface ripples are generated periodically at a rate of one every 0.8 microseconds, implying that a surface wave is produced for every 0.4 mm of crack advance. The surface morphology of this fracture process has a

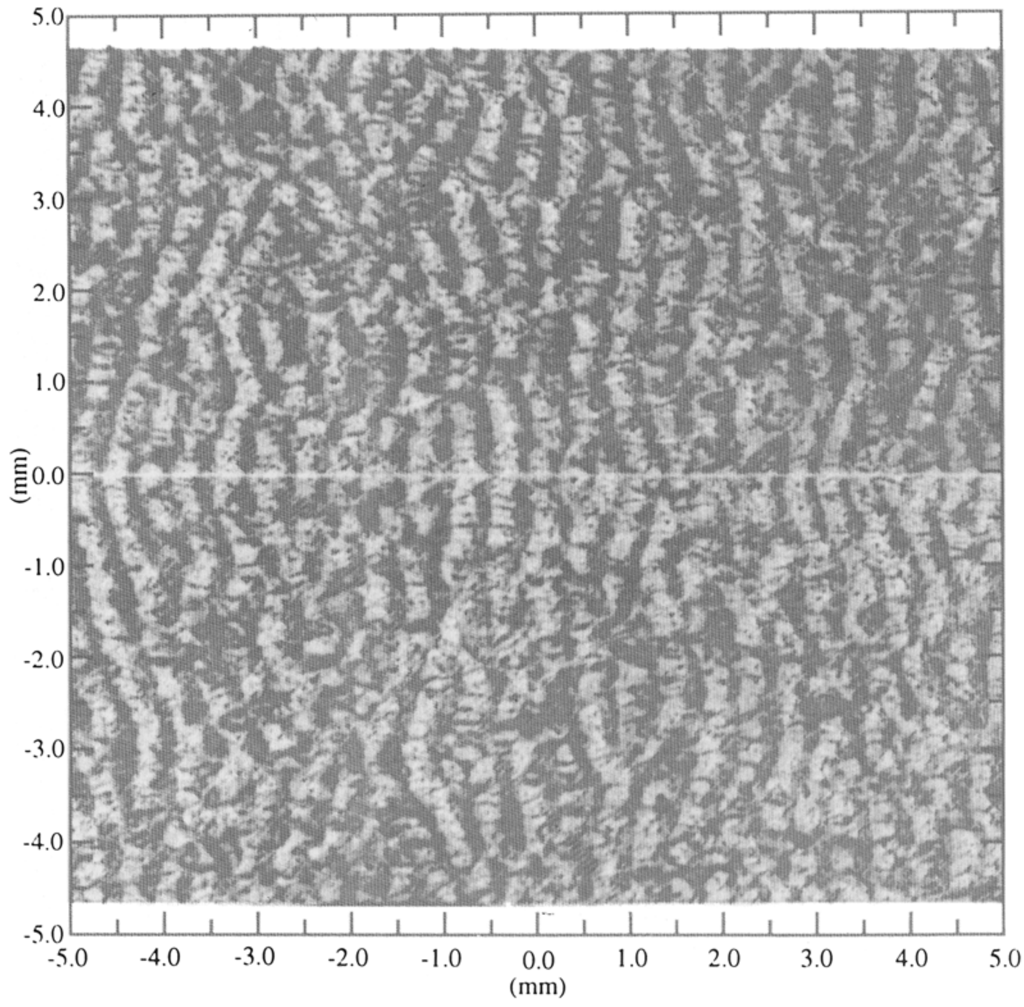

Fig. 6. Fracture morphology of both separated halves of the specimen shown in Fig. 5. This surface was produced by a crack propagating from left to right at an average velocity of 0.5 mm/μs in a 4.59 mm thick plate of PMMA.

corresponding simple 0.4 mm periodic, approximately straight, ripple structure that is on average parallel with the plate normal.

The temporal frequency of these measurements are about an order of magnitude too coarse to trace the details of a single period in the fracture process. However, some additional information about how the crack proceeds can be gleaned from the detailed spatial resolution. In particular the crack appears to move and generate this periodic behavior with an oscillation in the propagation direction. The surface ripples radiating from the crack tip appear symmetric with respect to the average crack propagation direction. Further, the morphology of both halves of the specimen are approximately mirror images. This is suggestive of an accelerating-decelerating, or discontinuous process with a constant crack direction. This morphology opposes a crack extension mechanism that incorporates a rapid oscillation in the propagation direction.

4. Discussion of results

Experiments employing photoelasticity tend to uphold a relationship between the stress intensity and crack velocity. The fracture velocity has been expressed as a continuous function of the stress intensity [2, 3]. Other measurement techniques (e.g. transmitted caustics) are less supportive of such a function [4]. Plainly, part of the muddle in the experimentally determined stress intensity vs. velocity relationships [2–4] rests on the spatial precision of the measurement technique. An experimental method with fine spatial resolution, such as transmission caustics, will record the inherent unsteady nature of the fracture process especially near the crack tip [10].

The rapid fracture of PMMA is particularly simple in that is consists of a periodic agglomeration of especially large microstructural phenomena. As one might suspect owing to the extensively studied dynamic fracture morphology of PMMA the rippled surface shown in Fig. 6 is not unique to this experiment [13–16, 21]. Indeed, re-examining the specimens of a series of transmissive caustic-infinite plate tests in PMMA [18] reveals periodic markings at crack speeds above 0.3 mm/μs. These markings had previously been attributed to waves reflecting from the boundaries and Wallner lines initiated from surface inperfections rather than inherent to the fracture process [15, 16]. In the present simulation of an infinite plate there are no discernible surface imperfections greater than a few micrometers. The only remaining macroscopic length scale local to the propagating crack is the plate thickness.

Accepting that the morphology is indicative of the local fracture phenomena, it is a continual goal to determine the scaling of the surface features with some external parameter. In dynamic fracture mechanics the morphology of PMMA has been categorized in terms of fracture velocity [16], and for Homalite-100 the surface roughness was classified in terms of local dynamic stress intensity [4]. Since some features of the PMMA fracture surface are easily quantifiable above velocities of 0.3 mm/μs aspects of the scaling of the surface morphology can be readily determined. Figure 7 shows the dependence of the band size divided by the specimen thickness as a function of crack velocity divided by the Rayleigh wave speed of the quiescent material. Here the thickness is nominally 4.5 mm and the Rayleigh wave speed is taken as 1.04 mm/μs. Figure 8 displays the same normalized band size against the dynamic stress intensity determined by caustics, divided by the static stress intensity. Here the static stress intensity is taken as $1.05 \times 10^6 \text{ Pa}\sqrt{\text{m}}$.

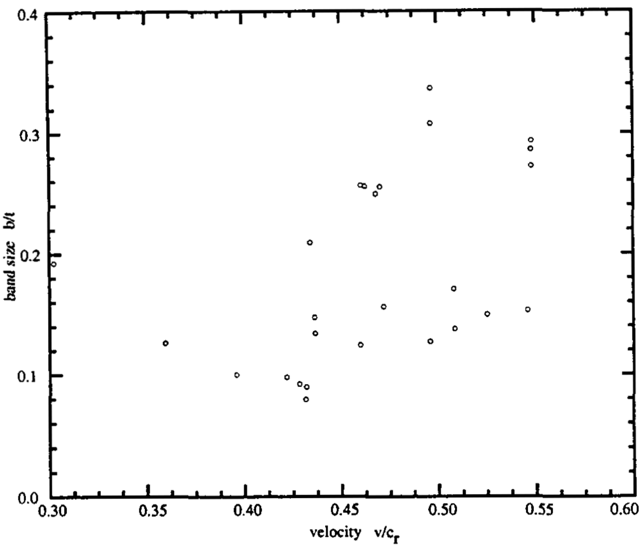

Fig. 7. Dependence of the normalized fracture morphology spatial period on the normalized crack velocity for PMMA.

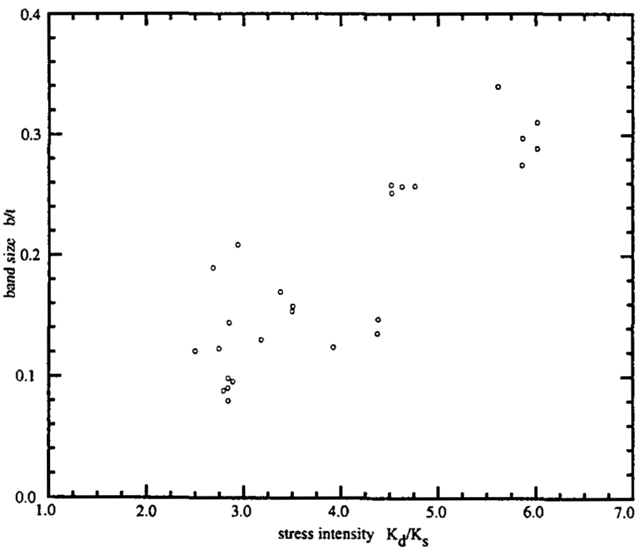

Fig. 8. Dependence of the normalized fracture morphology spatial period on the normalized stress intensity factor for PMMA.

The band size tends to increase with both stress intensity and crack velocity. However, there is considerable scatter in the velocity dependence. Indeed if a straight line is fitted to the data to minimize the sum of the square error, the correlation coefficient in the velocity representation is 0.2 while for the stress intensity characterization the correlation is 0.8. Thus the stress intensity characterization appears to be more reliable, and is therefore preferable.

The unsteady fracture process leading to a banded morphology is not limited to the dynamic fracture of PMMA [22]. Hertzberg et al. have measured discontinuous growth in fatigue tests of various amorphous polymers [23]. One band takes multiple fatigue cycles to form and the band size depends on the applied stress intensity as shown in Fig. 9.

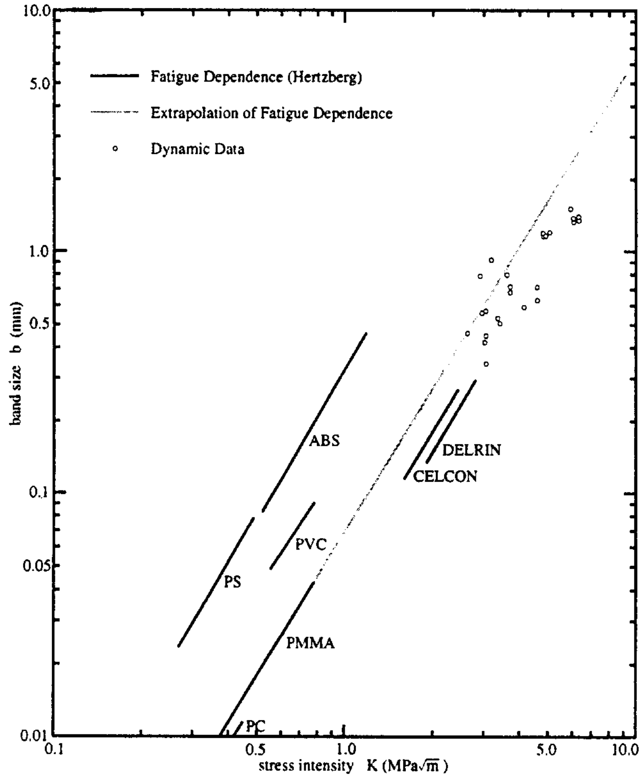

Fig. 9. Dependence of the fracture morphology spatial size, in both a fatigue and dynamic fracture environment, on ΔK_f for five amorphous polymers, two grades of polyacetal (Celcon and Delrin) [23], and on K_d for PMMA.

The proposed mechanism for this process is a crack forming a craze [24], with the craze ultimately failing to form a new crack [25]. The discontinuous growth occurs when the crazed material fails catastrophically.

This crazing mechanism is more distributed and naturally occurring, but similar to the artificially introduced late breaking ligaments examined by Shukla and Dally [12] in dynamic fracture. The data from Fig. 8 are plotted with Hertzberg's data in Fig. 9. The band size extrapolated from the fatigue tests to the higher stress intensities of the dynamic measurement is, within the experimental scatter, in remarkable agreement in both magnitude and slope. This agreement in scaling of the fracture morphology between markedly different experiments lends credence to the hypothesis that cracking occurs over a material intrinsic length that is promoted to stress [4].

These tests were all performed with specimens that were nominally 4.5 mm thick. Green and Pratt [16] note a similar fracture morphology in PMMA specimens that were nominally 12.7 mm thick. However, the bands in their fracture surface morphologies lie distinctly at a constant angle of $\pm 66°$ with respect to the propagation direction. The explanation for this angle is that the crack front is straight and is interacting with a shear wave from the plate surface. This shear wave roughens the fracture surface at the immediate intersection of the shear wave and crack fronts. The angle stays constant because of the rate dependence of the material properties [16]. Figure 6 has band features that are at angles of 60° to 90° (perpendicular) to the propagation direction. At higher stress intensities, the band size becomes an appreciable fraction of the plate thickness making angles less discernible. Presumably in the thicker specimens, the craze preferentially first breaks at the intersection of the specimen surface and the crack front. However, in thinner specimens or at higher stress intensities, the drawn out ligaments of the craze can break first in the interior as well as near the surface of the plate.

5. Conclusions

Dynamic fracture, especially at velocities approaching the wave speeds of the material can be non-steady. This non-steady behavior may arise due to an inherent non-continuous fracture process and needs to be addressed when comparing both theory and measurement.

The dynamic fracture process of PMMA at high stress intensities is particularly simple in that it is periodic and occurs over millimeter size lengths. The cracking appears to scale with the dynamic stress intensity and with the amplitude of stress intensity in fatigue tests involving crazing. Thus a craze mechanism may explain both the fatigue and dynamic fracture behavior of PMMA. Finally, Hertzberg's fatigue data [23] on other amorphous pclymers suggests that this periodic behavior over millimeter lengths can be found in other polymer systems in a dynamic fracture environment.

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