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An Ultrasonic Technique for Measuring Crack and Craze Velocities

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A technique is described which employs ultrasonic waves in order to monitor the velocity of a slowly propagating discontinuity in a material subjected to stress in a liquid environment. The technique is particularly useful in the study of environmentally induced crack and craze propagation in polymeric materials. This paper describes the equipment, its operation and some preliminary results for one particular application.

1. Introduction

Techniques for the determination of crack velocities have usually concentrated on measurements of high speeds, and low velocity measurements are considered to present no difficulty. The normal methods for measuring low speed crack propagation are optical, being based on the direct observation of the crack tip with a travelling or measuring microscope. Such methods tend to be time consuming, especially when a continuous record of velocity is required, and may be difficult to apply to opaque specimens if the surface crack is not clearly visible. This is particularly the case if the propagating discontinuity is a craze and not a true crack, as is often the case in polymeric materials. Direct visual observation is also complicated if the specimen is immersed in liquid, as for the study of environmental stress crazing or environmentally assisted fatigue.

For a variety of reasons, therefore, a new and automatic technique was sought for the continuous recording of low, and very low propagation velocities. The method described here was developed especially for the study of environmental stress cracking and crazing in polymeric solids, but could clearly be used in other situations where the specimen is immersed in a liquid.

The technique involves the repetitive ultrasonic scanning of the discontinuity by a traversing transmit/receive probe. The necessary acoustic coupling between transducer and specimen is provided by the immersion liquid, and involves no mechanical interaction between the two.

The ultrasonic waves are reflected from the discontinuity interface, but the reflection dies away as the traversing probe passes the discontinuity growth tip. Although the absolute position of this tip cannot be located precisely by the reflection, because of the large beam width, *changes* in its position (and hence its velocity) can be very accurately measured, as will be seen.

Ultrasonic methods have previously been used for flaw detection and in one case a stationary ultrasonic transducer has been employed to determine the rate of crack propagation in low cycle fatigue tests [1]. However, to the authors' knowledge, a scanning ultrasonic technique has not previously been used to determine the velocity of propagating cracks and crazes.

2. Equipment

The general layout of the equipment is indicated schematically in fig. 1. In essence the equipment comprises a loading frame, a temperature controlled immersion chamber, an ultrasonic probe traversing rig and the attendant ultrasonic generator, display and "gating" units, together with the recording and traversing control systems.

2.1. The Loading Frame and Immersion Chamber

The loading frame is shown in fig. 2. The specimen (typically having the dimensions 0.16 × 0.07 × 0.001 to 0.005 m) is axially loaded in simple tension by a capstan head which is made to deflect a calibrated beam, the displacement of which is measured by a sensitive dial gauge. The frame is most effective for materials that do not creep appreciably under the test conditions; glassy polymers under the low stresses normally employed, are one such example. The frame may

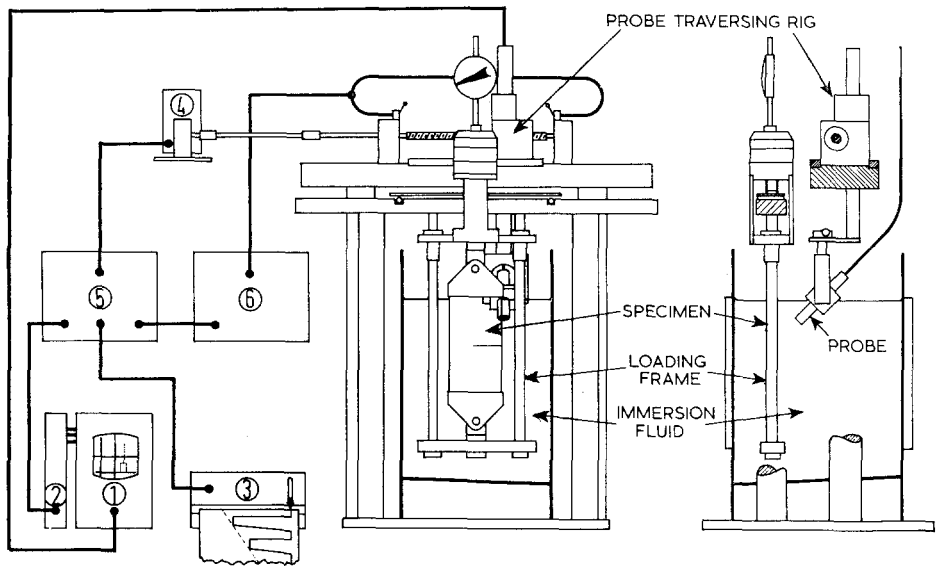

Figure 1 General layout of equipment for measuring crack and craze velocities by the scanning ultrasonic technique. (1) Ultrasonic pulse generator and display. (2) Ultrasonic signal "gating" unit. (3) Variable, constant speed pen recorder. (4) DC motor and gear box. (5) and (6) Control cabinets, housing: Relay reversing system, pen and traverse time delays, ultrasonic signal voltage integrator and stabilised power supply.

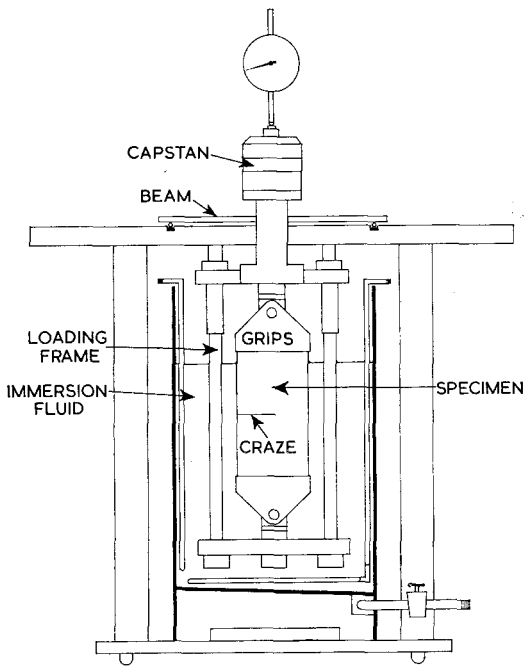

Figure 2 Specimen loading frame and immersion chamber.

be considered a "hard machine" and should the specimen creep the decrease in load will be evidenced by movement on the dial gauge, and can be corrected. If creep becomes inconveniently fast, the loading frame can be simply modified to apply "dead load". The complete loading frame resides within a lagged and stirred temperature controlled immersion chamber containing the liquid environment under study.

2.2. The Ultrasonic Probe Traversing Rig

The ultrasonic probe traversing rig, shown in figs. 3 and 4, is mounted in a parallel plane behind the loading rig. Suspended from the traversing block is the ultrasonic probe which is positioned within the immersion chamber. The probe may be adjusted, during the focusing procedure, in the vertical, the horizontal (normal to the specimen) and the angular positions with respect to the specimen. Traversal of the probe is obtained by movement of the traversing block along a "V" guide by a screw thread which is rotated by a constant speed motor. When the traversing block actuates a micro-switch at one end of its travel the motor is cut out and the block is stopped, a relay system reverses the polarity to the motor and a time delay from 1 sec to 5 h, as required, is engaged. On expiration of the time delay period, the motor is once again brought into action and the probe traversing block travels back down the screw thread to the micro-switch at the other end of its travel, when the same operation is repeated.

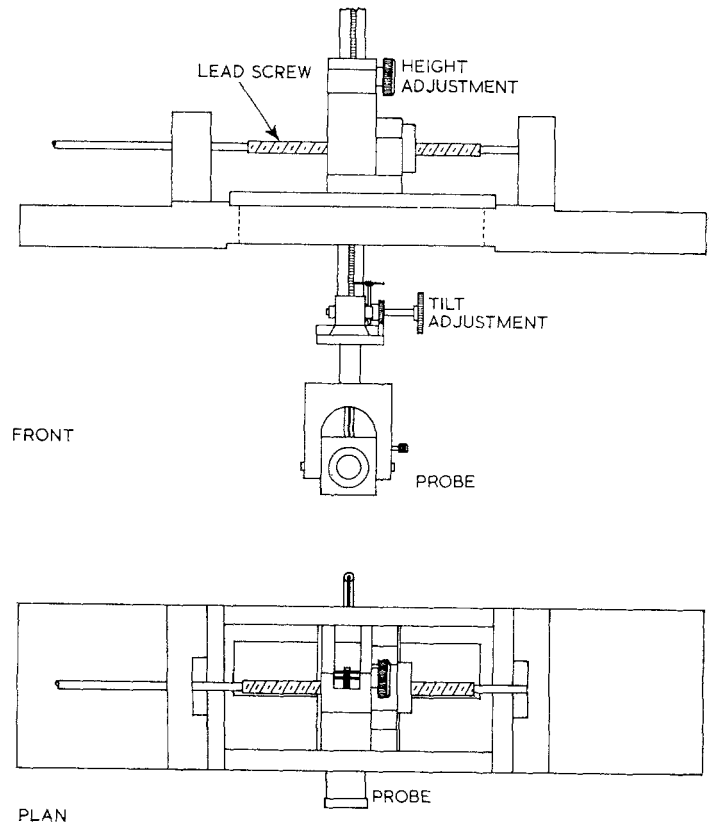

Figure 3 Ultrasonic probe traversing rig; front elevation and plan.

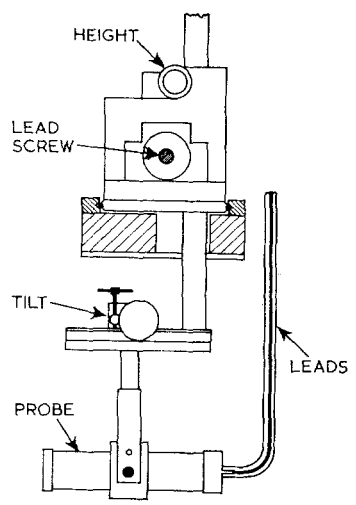

Figure 4 Ultrasonic probe traversing rig; side elevation.

2.3. The Ultrasonic Probe

The ultrasonic transducer is constructed of lead zirconate and is specially designed for use as a water immersion probe. The complete probe has been sealed into a tube with the transducer face only exposed, and can be immersed in the various liquid environments employed. The transducer is excited by an extremely short dc pulse such that it vibrates at a fundamental frequency determined by the thickness of the ceramic. The single probe, when excited, produces a short burst of ultrasonic energy and may then act as a receiver for the reflected signal. The pulse length is short and consists of about three cycles of the high frequency radiation; the pulse repetition frequency employed is 1000 Hz. The probe ("Ultrasonoscope" special high temperature working immersion probe) has a frequency of 5.0 MHz and a transducer face diameter of 0.015 m. The ultrasonic beam emitted by the transducer is not perfectly circular in cross section due to ceramic imperfections and probe manufacture requirements, but 99% of the beam width has been shown to give negligible divergence at distances up to 0.08 m from the transducer face.

3. The Ultrasonic Technique

This study employs the "A" scan pulse-echo presentation ("Ultrasonoscope" Mk. 2C Flaw Detector) which indicates both the amplitude of the reflected signal and the distance of the discontinuity from the transducer which remains constant due to the parallel/horizontal traversal of the probe with respect to the discontinuity.

3.1. Sensitivity

The amplitude of the reflected signal is an important factor in determining the sensitivity of the technique and in the present study the transducer diameter, which is three to fifteen times as great as the discontinuity width, places a lower limit on the velocities that may be measured; the lower limit has been found experimentally to be of the order 0.01 μm sec^{-1}. The upper limit, determined by the ultrasonic probe traversal velocity is estimated to be of the order of 100 μm sec^{-1}. Both the upper and lower velocity limits may be increased, in the former case by employing faster traversal velocities and in the latter by employing a transducer diameter commensurate with the discontinuity width.

Other factors will influence the sensitivity of the technique, the most important of which is the voltage/time gradient of the voltage integrator which feeds a pen recorder.

3.2. Signal "Gating"

Consider the ultrasonic transmit/receive probe angled and positioned to give the greatest amplitude of the reflected signal from a linear discontinuity. A balance between signal gain and attenuation must be used to ensure that the "background noise" does not interfere with the reflected signal. The ultrasonic "gating" unit ("Ultrasonoscope" ALD4/2 Alarm Unit) provides the means by which the reflected discontinuity signal may be selected from other signals, and further, provides the means by which the fall of the signal amplitude is detected (i.e. "breaking the gate") as the probe beam passes through the discontinuity tip during scanning. (The "gate" signal itself may be set to any suitable level.) When the intensity of the reflected signal falls to the level of the "gate" signal, the "gate" is "broken" and a relay is actuated, triggering a voltage integrator. This gives rise to a linearly increasing voltage which is fed to a pen recorder. Scanning of a propagating discontinuity by the ultrasonic beam thus gives rise to a relative length/time curve, from which the velocity may be extracted (see section 5).

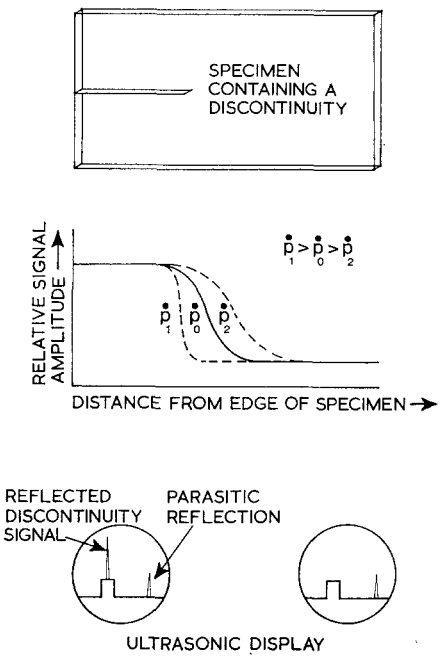

Figure 5 Reflected ultrasonic signal amplitude as a function of the distance from the edge of the specimen.

3.3. The Diffuse Ultrasonic Reflection at the Discontinuity Tip

The ultrasonic scanning technique for velocity measurement rests on the unimportance of the degree of diffuseness of the reflected signal amplitude, as the probe beam passes through the discontinuity tip region.

Fig. 5 indicates schematically the fall in signal amplitude as the finite diameter probe beam passes through the tip region of a hypothetically square fronted discontinuity tip. Because the tip is in motion, an increase in ultrasonic probe traversal velocity from $\dot{p}_0$ to $\dot{p}_1$ will decrease the diffuseness of the amplitude/distance transition, while a decrease in velocity to $\dot{p}_2$ will increase the diffuseness. However, provided the discontinuity tip does not change its shape during propagation, it does not matter what the ultrasonic probe velocity is, for on successive traversals the amplitude at which the signal "breaks" the "gate" remains constant. Similarly in respect of the discontinuity tip shape, provided it remains constant, the signal amplitude at which the "gate" is "broken" also remains constant, albeit that any tip shape other than a square front

leads to a greater degree of diffuseness of the amplitude/distance curve.

Thus, with the proviso that the tip shape remains constant during propagation, it can be seen that the "gate" effectively selects an arbitrary position, in the vicinity of the "true" discontinuity tip, to which all measurements of length are referred.

3.4. The Refraction and Reflection of Ultrasonic Waves

The velocity and direction of ultrasonic waves refracted in a medium are given by Snell's Law, and it is often the case that when ultrasonic waves pass from a liquid into a solid medium there occurs a critical angle of incidence for which the angle of refraction into the solid medium becomes 90°.

Longitudinal, transverse (shear) and surface waves may be propagated in or along a solid medium; each of these waves propagates at a different velocity for a given solid and hence exhibit differing critical angles of incidence. Thus, for example, in the case of ultrasonic waves incident at an ethyl alcohol/PMMA interface, longitudinal waves may be refracted in the PMMA up to angles of incidence of 26° to the normal, transverse waves up to 65° and surface waves from between 80 to 90° to the normal, at room temperature. Generally, in the cases of simple liquids and polymeric solids, transverse waves only are transmitted in the solid media through the angles 30 to 60° to the normal.

The present technique of discontinuity velocity measurement requires that the maximum signal amplitude be returned from the discontinuity surface to the ultrasonic probe, after refraction and reflection, such that incident angles at the solid interface in the range 30 to 60° are employed, giving rise solely to transverse waves in the solid medium.

4. Mode of Operation

Consider the probe to be traversing from right to left in fig. 1, where the discontinuity is growing in a horizontal mode due to the forces of tension. As the probe starts its travel from right to left then, at first no signal appears on the display along the time base at the position at which the discontinuity signal will eventually appear, since there is no reflecting surface. Later as it passes the "open" end of the discontinuity a signal appears on the display and as the signal "breaks" the

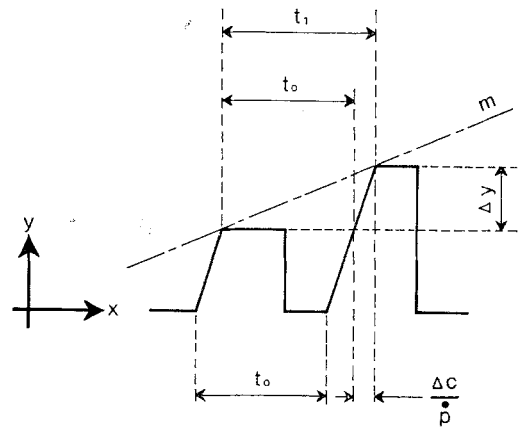

Figure 6 Schematic representation of the data recorded for two successive traversals by the ultrasonic probe of a propagating discontinuity.

"gate" the pen on the x-t pen recorder begins to move across the chart paper. The pen continues to move across the paper until the probe beam passes the tip of the discontinuity, at which stage the signal on the display falls out and a constant voltage is maintained to the pen recorder (i.e. pen stationary) until the traversing block actuates the left hand micro-switch and the pen falls to the base line on the chart; a time delay period ensues, after which the probe moves off in the reverse direction. During this time delay the discontinuity will have grown, so that on this traverse the probe will remain in the presence of the discontinuity for a slightly greater period of time, leading to an increased pen rise across the chart. A succession of traverses thus leads to a plot on the chart which possesses a slope; the height of each pen rise is proportional to the length of the discontinuity (plus an arbitrary, but constant "zero error") and so the slope yields the discontinuity velocity, after suitable calibration.

5. Retrieval of Velocity Data from the Recorded Chart Slope

Fig. 6 is a schematic representation of the data recorded for two successive traversals by the ultrasonic probe of a propagating discontinuity. From fig. 6:

$$t_1 = t_0 + \frac{\Delta c}{\dot{p}}$$

where t_1, the time for one cycle, is equal to t_0, the time for one cycle had there been no discontinuity growth during the cycle, plus $\Delta c/\dot{p}$ where Δc is the change in discontinuity length during the

cycle and $\dot{p}$ is the probe traversal velocity. The slope, m, is given by:

$$m = \frac{\Delta y}{t_1}$$

The pen velocity across the chart, $\dot{y}$, is given by:

$$\dot{y} = \frac{\Delta y}{t_1 - t_0} = \frac{\Delta y \,.\, \dot{p}}{\Delta c}$$

thus

$$\Delta y = m \,.\, t_1 = \frac{\dot{y} \,.\, \Delta c}{\dot{p}}$$

and

$$\frac{\Delta c}{t_1} = \dot{c} = \frac{m \,.\, \dot{p}}{\dot{y}}$$

When the slope is measured directly in chart units, then the propagation velocity is given by:

$$\dot{c} = \frac{m \,.\, \dot{p} \,.\, \dot{x}}{\dot{y}}$$

where $\dot{x}$ is the chart velocity.

Thus, with knowledge of the ultrasonic probe traversal velocity, the pen velocity across the chart and the chart velocity, then the discontinuity velocity, $\dot{c}$, is directly available through measurement of the chart slope.

6. Preliminary Results and Applications

6.1. Environmental Stress Crazing in the system PMMA/Ethyl Alcohol

Experimental results thus far have indicated the usefulness of the ultrasonic scanning technique for velocity data collection of environmentally induced stress crazing in polymeric materials. For example, a single edge craze grown in a sheet of polymethylmethacrylate immersed in ethyl alcohol at 30°C, under various loading conditions, has been shown to propagate at a constant velocity for each loading condition. It was first necessary to confirm that the ultrasonic irradiation does not modify propagation and alter its velocity. This was done by growing the craze for a period of time with the ultrasonics off and measuring its (constant) speed by travelling microscope. The transducer was then switched on with the probe stationary, and the tip region was subjected to continuous irradiation whilst visual velocity measurements were continued. No change in the velocity could be detected.

Fig. 7 reproduces the actual plot obtained for the above system, and it may be noted that constant velocity is soon attained after a decrease of load.

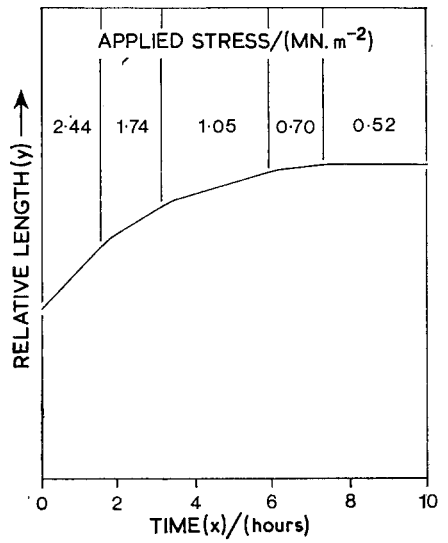

Figure 7 A representation of the plot obtained by the scanning ultrasonic technique for the system PMMA/ethyl alcohol at 30°C when a single edge craze is propagated under various loading conditions.

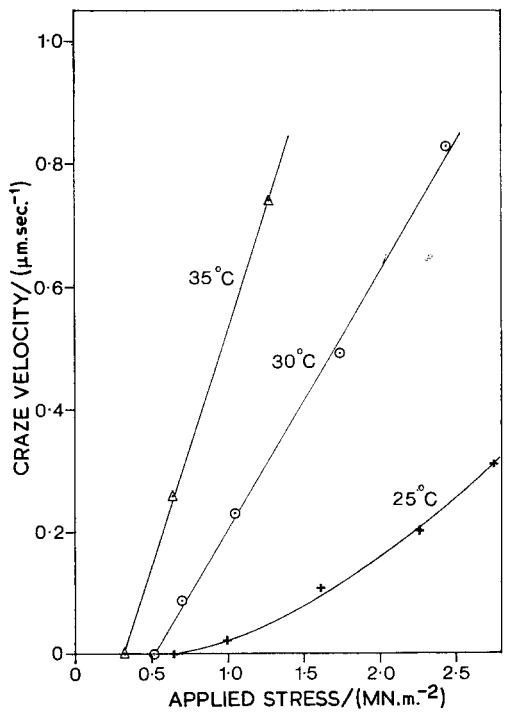

Figure 8 The ultrasonically measured craze velocity as a function of applied stress for the system PMMA/ethyl alcohol at 25, 30 and 35°C.

Fig. 8 shows a plot of the velocities obtained as a function of applied stress in the above system at three temperatures, 25, 30 and 35°C. The form of the plot is completely analagous to that found in the polycarbonate/alcohol system [2] and indicates a critical applied stress for craze propagation of 0.64, 0.52 and 0.32 MNm^{-2} respectively for the three temperatures.

Velocity data is at the present time being collected for the system PMMA/monohydric aliphatic alcohols over a range of temperatures. The results to date are found to be compatible with a previous study of craze propagation [3].

6.2. Applications

The scanning ultrasonic technique may be employed for the investigation of slowly propagating cracks and crazes in many materials in liquid environments, and lends itself to environmental fatigue testing as well as constant load tests. An important feature of the technique is that it is not limited to transparent polymers, and therefore filled or opaque, as well as transparent materials, may be investigated; it could therefore, prove suitable for studies in metals, concrete and ceramics.

Acknowledgements

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References

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