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Cyclic modulation of moving cracks in glassy polymers by ultrasonic shear waves

K. TAKAHASHI, K. MATSUSHIGE*, Y. SAKURADA
Research Institute for Applied Mechanics, Kyushu University, Hakozaki, Higashiku, Fukuoka 812, Japan

In order to explore the possibility of cyclic modulation of fast cracks in glassy polymers by ultrasonic shear waves, a comparison is made of fracture velocity values for PMMA and epoxy which were obtained simultaneously by ultrasonic fractography and high speed photography. A satisfactory agreement between the two sets of values confirms the applicability of the method to viscoelastic materials. In connection with the fractographical results, some advantages of this method are discussed.

1. Introduction

Moving cracks in glassy materials are occasionally deflected by acoustic waves transmitting within the materials. When the waves are intense enough, visible lines are left on the fractured surfaces. These lines are known as Wallner lines [1]. By using ultrasonic shear waves, Kerkhof [2, 3] obtained the artificial Wallner lines, or ultrasonic lines, which were utilized for precise determination of the fracture velocity in glasses. The Kerkhof method based on ultrasonic fractography has been applied by several authors to glasses [3] and to some crystalline materials [4, 5]. As far as its application to glassy polymers is concerned, a few attempts have been made preferentially for poly(methyl methacrylate) (PMMA) [6–10]. However, the application involved some difficulties. Serious wave damping occurs in viscoelastic materials, which made it hard to obtain clear ultrasonic lines that are dense enough and well identified for quantitative measurements. On the other hand, in the case when some repeated markings are produced in a modulation test, there should arise a question about the presence of reflected waves contribution which would result in an erroneous measurement. Furthermore, it is not rare that various kinds of Wallner-line-like markings are left on fractured surfaces of glassy polymers even without application of ultrasonics [11]. The pseudo Wallner lines have sometimes spacings comparable to those obtained from typical ultrasonic modulation tests [11]. These situations offered doubt as to certainty of the origination of real ultrasonic lines in polymers. As to the last point, in question, the experimental findings obtained from previous experiments by Takahashi *et al.* [9] gives a positive answer; the amplitude of ultrasonic lines becomes smaller as a function of distance from a wave transmitter [9], and the spacing of the lines decreases when the frequency of waves is increased [10]. However, in order to extend a more reliable application of this method to polymers, it was deemed necessary to confirm directly the possibility of cyclic deflection of moving cracks in response to high frequency shear waves.

In the present study, the confirmation is attempted by comparing fracture velocity values for PMMA and epoxy obtained by the Kerkhof method with those obtained simultaneously by high speed photography.

2. Experimental procedure

Single edge cracked tensile specimen plates of PMMA (Acrylite S-001) and epoxy (high temperature hardened Araldite B-TH901) with dimensions of 180 mm in length, 35 mm in width and 5 mm in thickness were used in the present experiment. Pre-cracking was made by chisel impact followed by fatigue notching under 120 Hz tensile

*Presently, Department of Applied Science.

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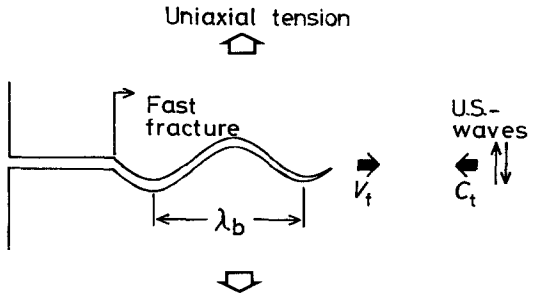


Figure 1 Cyclic modulation of a moving crack by ultrasonic shear waves.

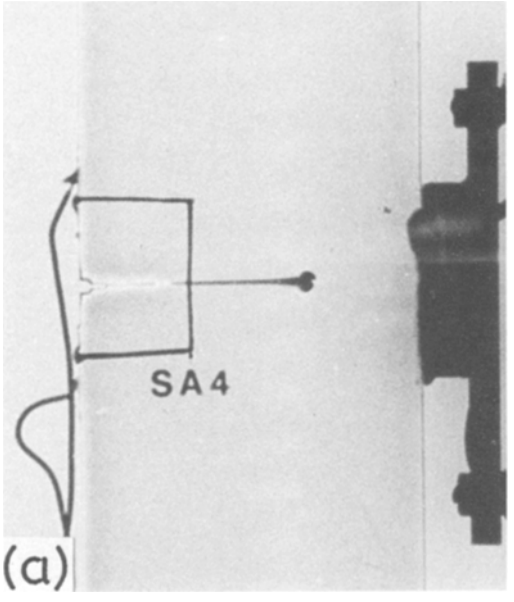
oscillation to the crack length of 8 to 9 mm, i.e. about one-fourth of the specimen width. An ultrasonic transducer, composed of a *Y*-cut quartz element and a piece of an aluminium transmitter, was glued to the opposite edge of the specimen so that its oscillation direction coincided with the direction of uniaxial tension applied to the specimen. Two ultrasonic frequency bands, 600 to 1200 kHz and 3.6 to 3.7 MHz, were used for the present experiment.

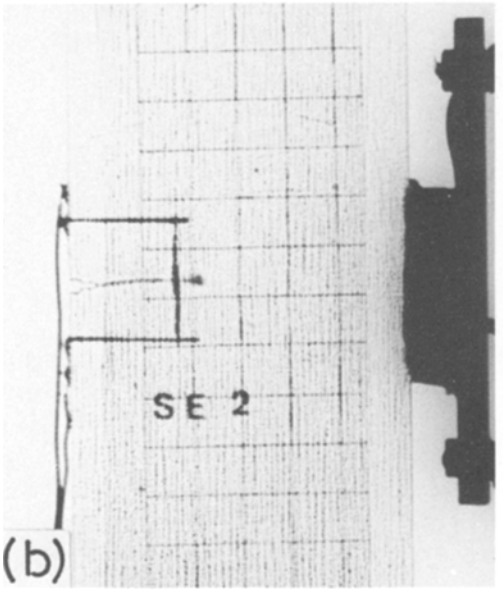
If we assume that the crack is cyclically deflected in response to the cyclic change of principal stress direction at the crack tip due to the shear wave modulation as shown in Fig. 1, the fracture velocity v_f is given by the following relationship

$$v_f = \frac{\lambda_b \nu_t}{1 - \frac{\lambda_b \nu_t}{c_t}} \quad (1)$$

where λ_b is the wavelength, or spacing, of the artificial Wallner lines, ν_t and c_t are frequency and the phase velocity of the ultrasonic waves, respectively. The c_t was measured by the sing-around method using 2 MHz waves, and the values of 1490 and 1070 m sec^{-1} were obtained for PMMA and epoxy at room temperature (23° C), respectively.

Simultaneous v_f measurements by high speed





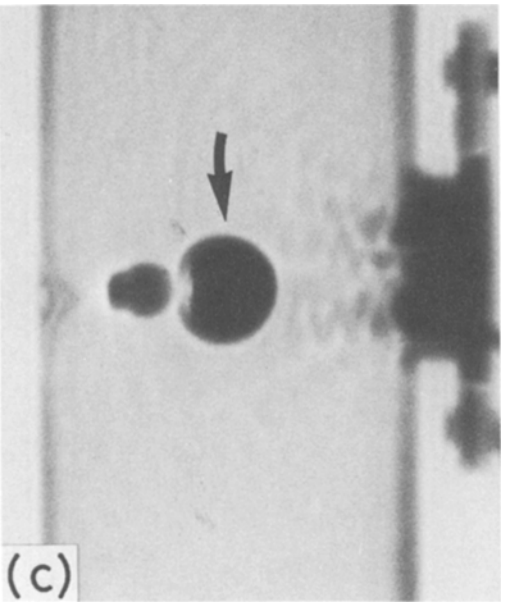


Figure 2 (a) and (b) are examples of high speed photographs for PMMA and epoxy specimens shown in Figs. 3 and 4, respectively, (c) is a high speed shadowgraph of another PMMA specimen.

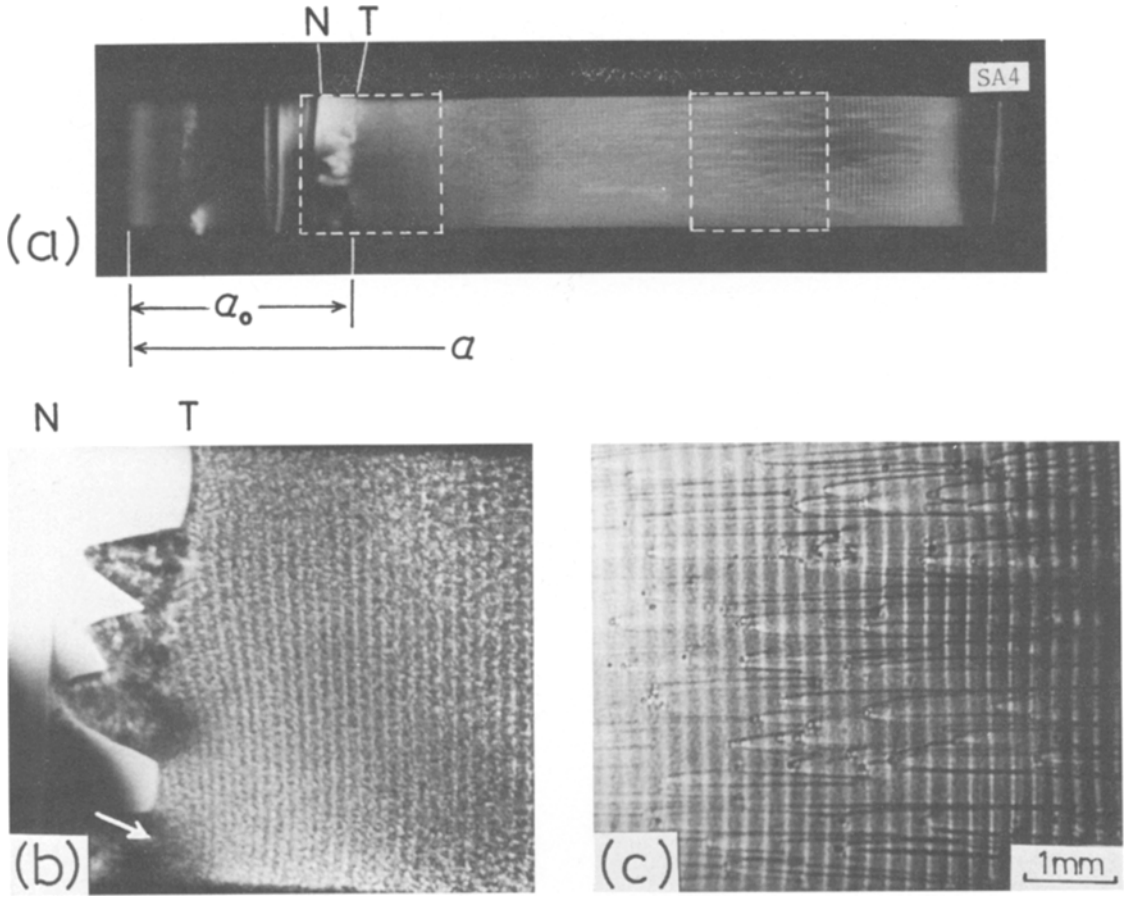


Figure 3 (a) A fractured surface of PMMA (test frequency, 870 kHz). (b) and (c) are enlarged pictures of the dotted areas in (a).

photography were carried out with a Cranz–Schardin camera. A conducting silver paint line glued on a specimen surface was used to trigger the light source equipment.

3. Results and discussion

Some examples of high speed photographs are presented in Fig. 2. Figs. 2a and b represent PMMA and epoxy specimens, each obtained from a series of 24 frame pictures, respectively. Fig. 2c is a shadowgraph of a PMMA specimen, where stress intensification around a running crack is visualized by a caustic (see arrow) and presence of 870 kHz shear waves emitted from the transducer is also discernible.

Fractured surfaces of the specimens given in Figs. 2a and b are shown in Figs. 3 and 4, respectively. Here N denotes the fatigue pre-crack front, T indicates the slow to fast transition location, a_0 is the crack length at the instability onset and a is the total crack length. From the enlarged pictures shown in Figs. 3 and 4, a number of parallel lines traversing in the direction of specimen thickness are discernible. These are the lines which have been assumed to be artificial Wallner lines. If we take the distance between adjacent lines as λ_b, we can obtain values of v_f from Equation 1. These values are plotted with open circles against the fast crack length $a-a_0$ in Fig. 5. Values of v_f determined by high speed photography are also plotted in the same figure with solid circles for comparison. In the experiment, in order to make the comparison more reliable, two kinds of frequencies for one polymer (PMMA) and two kinds of polymers for a similar frequency (860 to 870 kHz) were adopted. It may well be said that the agreement between two sets of v_f values obtained by the quite different methods is satisfactory. That the agreement is obtained independent of frequencies and polymers

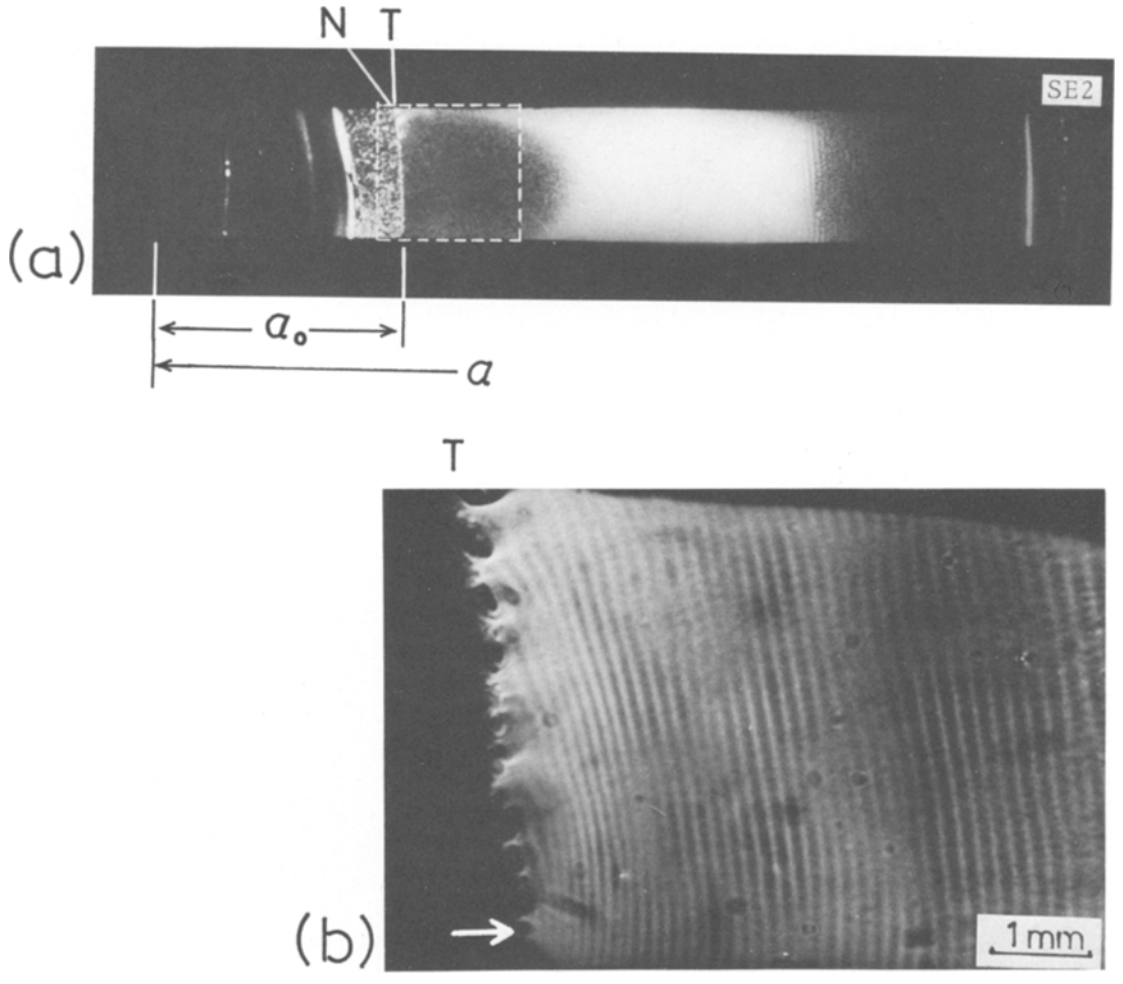


Figure 4 (a) A fractured surface of epoxy (test frequency, 860 kHz). (b) is an enlarged picture of the dotted area in (a).

confirms our view that the parallel lines left on the fracture surfaces in Figs. 3 and 4 are surely artificial Wallner lines originated by cyclic modulation of cracks.

It is interesting to see the profile of the ultrasonically modulated fracture surface. The profile can be obtained by interference microscopy [9] if the spacing is not too much for the microscopic observation and if the fracture surface is flat enough for focusing. A high sensitive roughness meter may also be employed for the purpose. In Fig. 6 is presented an example of roughness measurements, where PMMA fracture surface profile obtained from a 870 kHz test is given. The modulation intensity, i.e. a height from valley to mountain, in this case is about 200 nm, which is of the same order as the values optically determined in a previous experiment [9]. We can see that the profile is approximately sinusoidal.

Concerning its application to fracture velocity measurements for glassy polymers, several advantages of the Kerkhof method may be pointed out. First, because this method is free from the synchronization problem stated below, fracture velocities at transient stages such as instability onset, crack arrest and Charpy impact may be determined precisely with the resolving power of the line spacing. In Figs. 3 and 4 ultrasonic lines are separately discernible at a location just behind the instability line; it may well be said that in these cases instability took place almost instantaneously within one line spacing (about 100 μm). Fracture velocities determined just after the onset of instability for PMMA and epoxy in Figs. 3b and 4b (see arrow) are 135 and 95 m sec^{-1}, respectively. Usually it is very difficult to determine the starting velocity by high speed photography or by any other method because of the synchronization

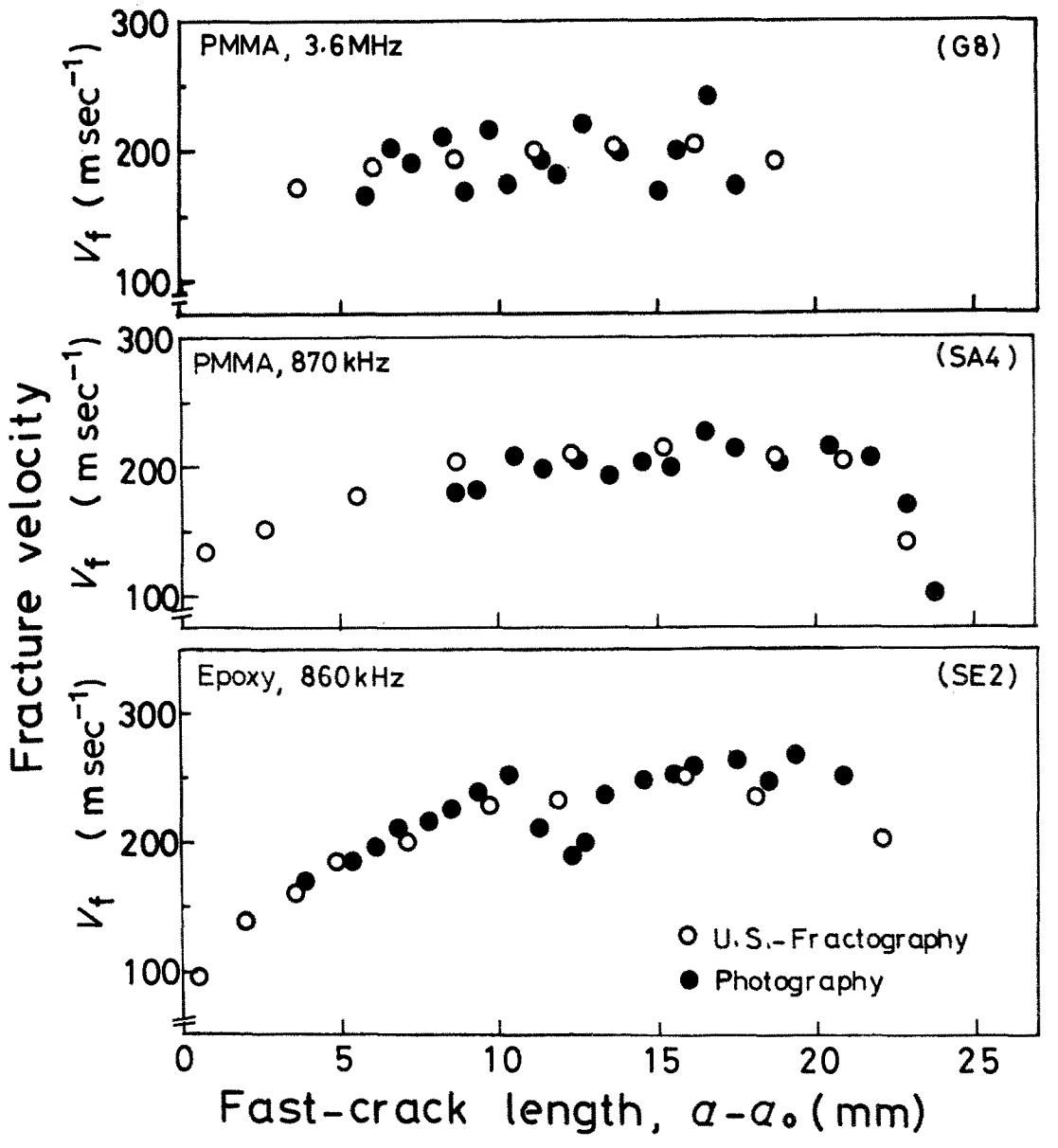


Figure 5 Results of fracture velocity measurements by ultrasonic fractography and high speed photography.

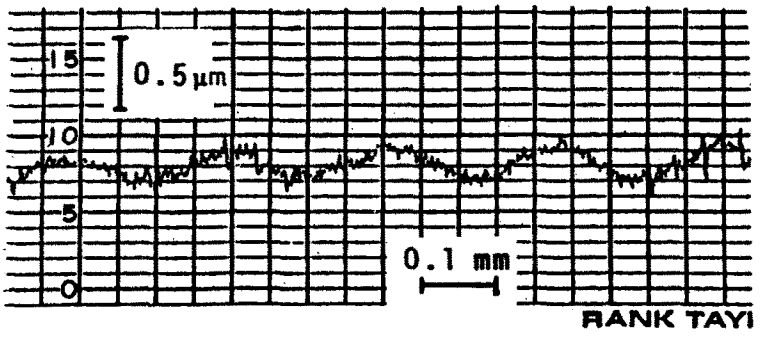


Figure 6 An example of the roughness profile of an ultrasonically modulated fracture surface of PMMA (870 kHz).

problem; the length of the slow fracture area scatters from specimen to specimen, and even if it does not scatter some limited time is needed for the activation of electric circuits, which would miss the instability instance. The lack of v_f data by high speed photography at an early stage of the measurement in Fig. 5 is due to these reasons. It should be noted here that, in contrast to the values obtained above, initial velocities given by high speed photography for PMMA and epoxy are 180 and 170 m sec^{-1}, respectively.

Secondly, while almost all other conventional methods are available only for one-dimensional crack propagation, this method can afford two- or three-dimensional fracture velocities [3]. When the fracture velocity is far less than wave velocity in the case of Fig. 1, the temporal shape of the fracture front can be determined by the ultrasonic lines. Naturally the exact location of the instability point can be known from the first ultrasonic line.

Thirdly, because this method is based on a kind of absolute measurement, it presents reliable fracture velocity values for calibration of other methods. It seems clear now that the scatter of v_f values by high speed photography seen in Fig. 5 does not reflect the real velocity change in each specimen, but is caused by some experimental errors. The errors are assumed to be caused mainly by the uncertainty in the visual determination of a crack tip in a film under an optical magnifier. The more increased spacial resolution we want, the more the scatter of the v_f values is unavoidable. Probably the conducting line method should have yielded less reliable v_f values than high speed photography, due probably to scatter in the simultaneity of arrival of a crack with electrical breakdown of the conductive lines on a specimen surface. Detailed results of the fracture velocity measurement for acrylic polymers by ultrasonic fractography will be published elsewhere.

4. Conclusion

It has been shown that ultrasonic fractography can be applied to glassy polymers such as PMMA and epoxy. Use of this method is advantageous especially for fracture velocity measurements at the instability onset and other transient stages where precise measurement by other methods are difficult. For its accuracy endowed by nature, it is also useful for calibration of their methods for fracture velocity measurements.

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