OPTICAL MEASUREMENT OF STRESS WAVES AND RAPID CRACK PROPAGATION IN THE TIME DOMAIN OF MICROSECONDS

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ABSTRACT

Interferometry is applied to taking photographs of stress waves emitted from crack tips which are moving in PMMA specimens at a speed of 500m/s or more. The cycles at which the crack tips emits the stress waves are measured from the photographs. It is confirmed that the cycle is of the order of hundreds nanoseconds. Furthermore, a method of high-speed holographic microscopy is developed and applied to take two successive microscopic photographs of a crack tip that is propagating dynamically. The method is one of the angular multiplexing holography. In the present study the time interval between the two frames is at 1μs or more. The high-speed holographic microscopy makes it possible to measure the extension of the crack and to obtain the crack speed in the time domain of microseconds.

KEY WORDS

Dynamic Fracture Mechanics, Rapid Crack Propagation, Stress Waves, Brittle Fracture, Optical Measurement, High-Speed Holographic Microscopy, Pulsed Holography, Interferometry.

INTRODUCTION

When a brittle material is broken by external force, there often appear cracks which propagate at a speed of several hundred m/s or more. It is known that the fast propagating crack tips emit stress waves. Washabaugh and Knauss (1993) measured the cycle at which the stress waves are emitted from the tips of fast propagating cracks in PMMA, and it was at 0.8μs. They furthermore pointed out that the emission of the stress waves and the shape of fracture surfaces indicate non-steady, periodic and perhaps discontinuous fashion of dynamic crack propagation. This is an interesting subject on dynamic fracture mechanics. However, there is no method which can successively observe the rapid crack extension in the time domain of microseconds or sub-microsecond.

There are two difficulties on photographing fast propagating cracks. (1) Crack opening displacement is so small that microscopic photography is required. (2) No one can exactly focus a conventional microscope on the surface of a specimen, because the specimen surface vibrates when the specimen fractures. One of the authors has studied several methods of pulsed holographic microscopy (PHM) which can solve the above difficulties and take instantaneous microscopic photographs of rapidly moving crack tips (Suzuki, 1988, 1990a, b, 1991). The PHM has much higher spatial resolution than the other optical methods used in dynamic fracture research. It can find the crack tip positions accurately and measure crack opening displacement or craze opening displacement of fast propagating cracks. However, PHM is a method of instan-

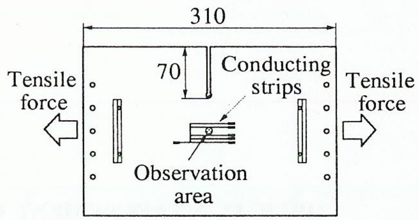


Fig.1 The PMMA specimen.

taneous photography, that is, it takes only one picture during a dynamic fracture event. In order to take successive photographs of a fast propagating crack, it is necessary to develop the pulsed holographic microscopy to high-speed holographic microscopy.

In the present study, measured are the time intervals at which stress waves are emitted from crack tips moving dynamically in PMMA specimens. Interferometry is used with the optical system of pulsed holographic microscopy. It is confirmed that the cycles at which the crack tips emits the stress waves are of the order of hundreds nsec. Furthermore, the present study develops high-speed holographic microscopy which can take two frames successively. The time interval between the frames is at 1μs or more. The method can accurately find the position of a crack tip in PMMA and measure the crack extension in the time domain of microseconds.

PMMA SPECIMEN

Figure 1 shows the transparent PMMA specimen used in the present study. Tensile force is applied to the specimen and a crack arises at the tip of the notch of 70mm long. The crack propagates toward the observation area at a speed of several hundred m/s. When the crack is running in the observation area, one or two successive photographs are taken with the methods of holographic microscopy. The crack cuts the five conducting strips on the specimen, and the signal of the cutting gives us the propagation speed of the crack. The cutting of the second conducting strip indicates the invasion of the crack into the observation area.

MEASUREMENT OF STRESS WAVES EMITTED FROM CRACK TIPS

Figure 2(a) shows the holographic optical system used for the measurement of stress waves emitted from fast running crack tips. A crack propagates in the PMMA specimen perpendicularly to the paper plane. When the crack is running in the observation area, the pulsed ruby laser PL oscillates once and emits a pulsed laser beam of about 30ns duration. The laser beam is divided into two parts by the beam splitter BS1. The beam transmitted through the beam splitter becomes a parallel light beam and falls onto the photographic plate HP obliquely. This is the reference beam. The light beam reflected from the beam splitter BS1 becomes a parallel light beam and impinges on the specimen surfaces perpendicularly. As shown in Fig.2(b), the light beam is reflected either by the front surface or by the back one of the specimen. The two reflected light waves, E_A and E_B, interfere with each other and make, around the crack tip, interference fringes which show the change of the thickness and the refractive index of the specimen due to stress concentration near the crack tip. The two light beams reflected by the specimen are reflected by the beam splitter BS2, make the real image RI of the crack and interference fringes, and, falls onto the photographic plate HP. This is the object beam. As described above, the optical system in Fig.2 records the crack and interference fringes as a hologram.

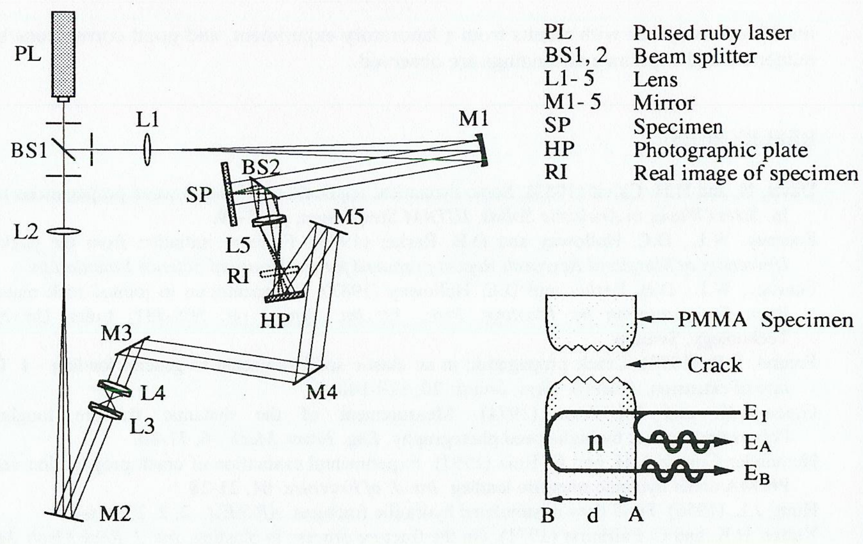


Fig.2 (a) The optical system for holographic recording. (b) Interference between the light wave reflected by the front surface and that reflected by the back one.

After development, illuminated with a c.w.He-Ne laser beam, the hologram reconstructs the real image of the crack and fringes, which is then photographed with a conventional camera.

Figure 3 shows an example of the cracks and interference fringes. The crack speed was at 510m/s. There appear the circular disturbances of interference fringes around the crack. These disturbances show the stress waves emitted from the crack tip. The speed of the stress waves shows that the stress waves are Rayleigh waves.

We measure the distances between the two successive stress waves on the photographs, and obtain the time intervals at which the stress waves are emitted from the crack tip. Figure 4 shows the results. The time intervals between two successive waves are less than 1μs and the average of them is at 0.60μs. This result is roughly in agreement with the result given by Washabaugh and Knauss (1993). The result may show that there exists a kind of unsteady propagation of the cracks in the time domain of sub-microsecond.

HIGH-SPEED HOLOGRAPHIC MICROSCOPY

As mentioned in the previous chapter, there is an interesting problem on unsteady behavior of fast propagating cracks in the region of sub-microsecond. In order to answer this problem, it is necessary to develop experimental methods which can measure the crack extension within the time domain of microseconds or sub-microsecond. In this chapter, a method of high-speed holographic microscopy which can measure the crack extension in the microsecond region is presented.

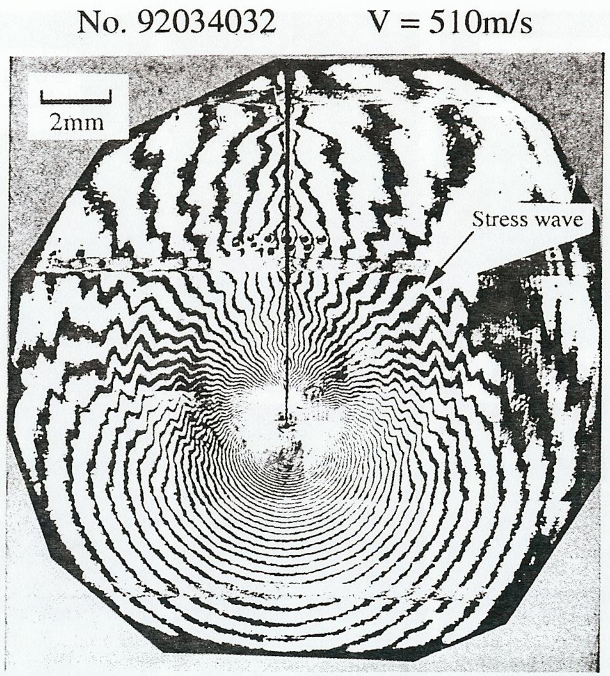


Fig.3 Stress waves emitted from the fast propagating crack in PMMA.

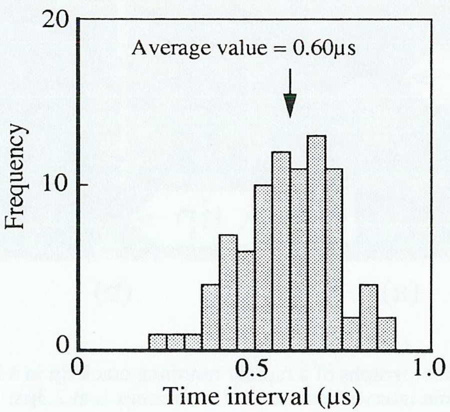
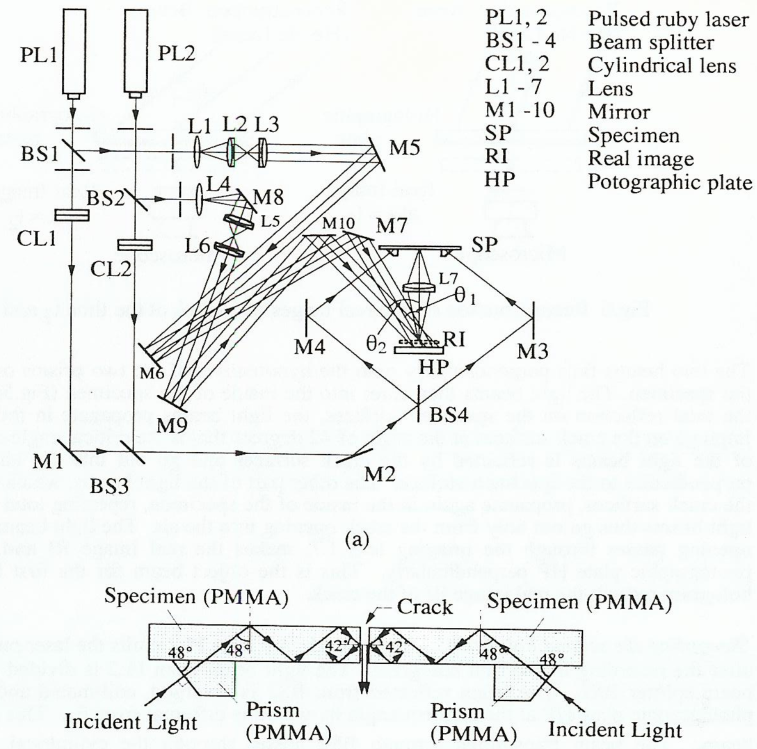


Fig.4 The frequency of time intervals between a couple of stress waves.



(b)

Fig.5 (a) Holographic recording of rapidly moving cracks in PMMA specimens.
(b) Propagation of light in a PMMA specimen.

Holographic Recording

Figure 5 shows the holography optical system to record a fast propagating crack. The optical system is of the angle multiplexing holography and can record two holograms of the crack on the photographic plate HP.

'Recording the first hologram'. When the crack is running in the observation area, the pulsed ruby laser PL1 oscillates and emits a laser pulse at the time t_1. The light beam from PL1 is divided into two beams by the beam splitter BS1. The beam reflected from BS1 is diverged and collimated and, falls onto the photographic plate HP at the incident angle θ_1. This is the reference beam for the first hologram recording. The light beam transmitted through the beam splitter BS1 becomes a gradually diverging beam by passing through the cylindrical lens CL1. It passes through the beam splitter BS3 and is divided into two beams by the beam splitter BS4.

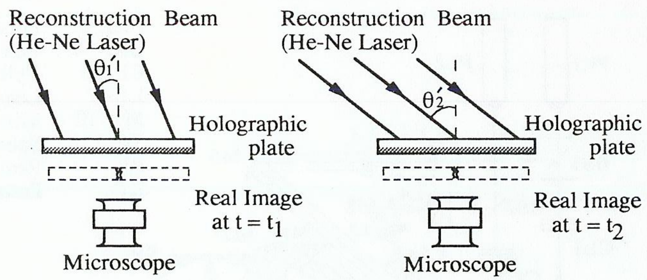


Fig.6 Reconstruction of two real mages of a crack at the time t_1 and t_2

The two beams falls perpendicularly onto the hypotenuses of the two prisms on the surface of the specimen. The light beams then enter into the inside of the specimen (Fig.5(b)). Repeating the total reflection on the specimen surfaces, the light beams propagate in the specimen and, impinge on the crack surfaces at the angle of 42 degrees that is the critical angle of PMMA. Part of the light beams is refracted by the crack surfaces and go out into the air approximately perpendicular to the specimen surface. The other part of the light beams, which are reflected by the crack surfaces, propagate again in the inside of the specimen, repeating total reflection. The light beams thus go out only from the crack opening into the air. The light beam from the crack opening passes through the imaging lens L7, makes the real image RI and, falls onto the photographic plate HP perpendicularly. This is the object beam for the first hologram. The hologram records the real image RI of the crack.

'Recording the second hologram'. The pulsed ruby laser PL2 emits the laser pulse at τ seconds after the recording of the first hologram. The light beam from PL2 is divided into two by the beam splitter BS2. The beam reflected from BS2 is diverged, collimated and, falls onto the photographic plate HP at the incident angle θ_2 which is different from θ_1. This is the reference beam. The beam transmitted through BS2 passes through the cylindrical lens CL2 and, gradually diverges perpendicularly to the paper plane. The light beam is reflected by the beam splitter BS3 and, follows the same path as the beam of the first recording passed. It becomes the object beam, and the crack at τ second after the first recording is recorded as the second hologram.

In the above procedure, angle multiplexing holography is used, that is, two holograms are superimposed on the photographic plate with the incident angles of the reference beams varied.

Reconstruction

Figure 6 shows the reconstruction of the two crack images. After development, the photographic plate is illuminated with the reconstruction beam that is a parallel light beam from a c.w.He-Ne laser (Fig.6). The incident angle θ_i' is given by the following equation,

$$\sin\theta_i' = \frac{\lambda_H}{\lambda_R}\sin\theta_i \qquad [\,i = 1 \text{ or } 2\,] \qquad (1)$$

where λ_H and λ_R is the wavelength of a He-Ne laser (633nm) and a ruby laser (694nm). If the incident angle of the reconstruction beam is at θ_1', then, the first hologram reconstructs the crack image at t=t_1. Similarly, illuminated at the incident angle of θ_2', the second hologram

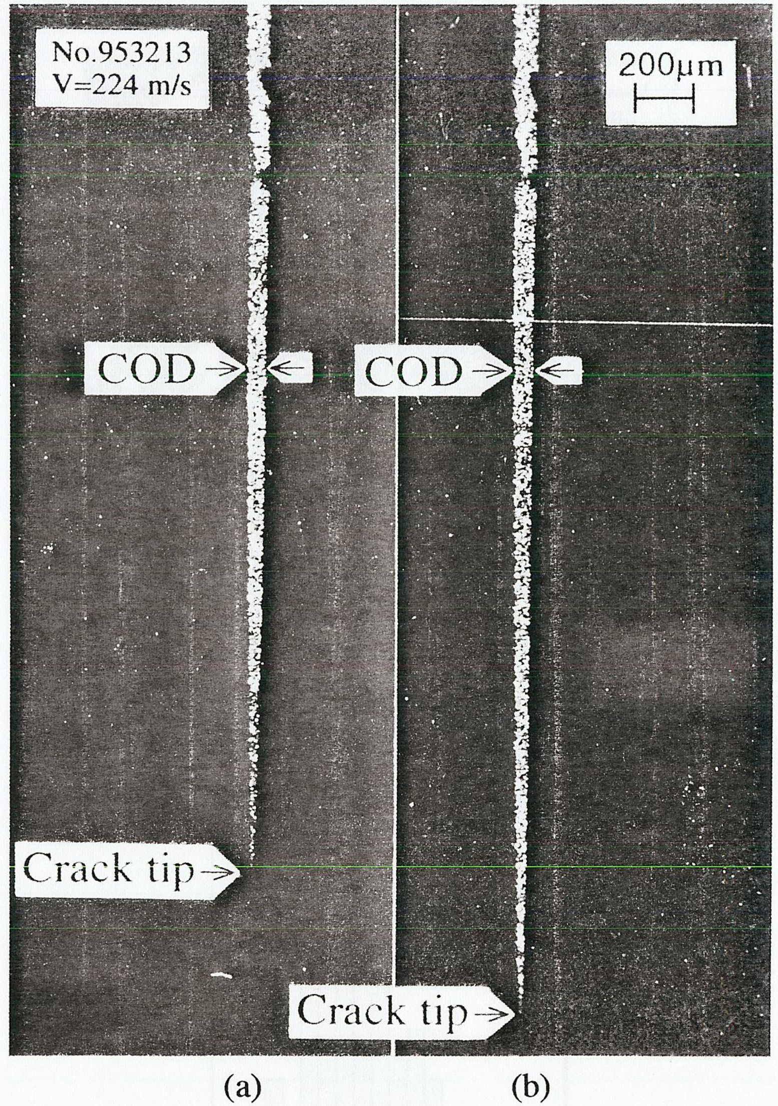


Fig.7 Two successive photographs of a rapidly runninng crack tip in a PMMA specimen. The time interval between the two frames is at 2.3μs.

reconstructs the crack image at $t_2=t_1+\tau$. These reconstructed images are magnified and photographed through a conventional microscope, and two successive pictures of a rapidly moving crack tip are obtained. There appear aberrations on the reconstructed images because the wavelength of the reconstruction beam is different from that at the holographic recording. The incident angle θ_i' given by Eq.(1) is the angle at which the aberration of the reconstructed image is minimum.

Results

Figure 7 shows an example of the two successive photographs of fast propagating cracks in PMMA. The bright regions are the crack. The time interval τ between the two frames was at 2.3μs. The crack propagated for about 486μm during the time interval. The crack speed was hence at 211m/s, which is roughly in agreement with the value of the crack speed, 224m/s, obtained from the cutting of the conducting strips. The quality of the reconstructed images from the superimposed holograms are as good as that from a single exposure hologram. As shown above, this method can measure the extension of a fast propagating crack within the time region of microseconds. The method also have the ability to measure the crack extension within the time domain of less than 1 microsecond.

CONCLUSIONS

(1) Fast propagating cracks emit stress waves whose cycles are about 0.6μs on the average. The result is roughly in agreement with that given by Washabaugh and Knauss (1993). The result may show the existence of a kind of unsteady extension of fast propagating cracks.

(2) A method of angle multiplexing holography is developed and applied to take two successive microscopic photographs of a fast propagating crack. The method can measure the extension of the fast propagating crack within the time domain of microseconds.

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