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Measurement of energy release rate and energy flux of rapidly bifurcating crack in Homalite 100 and Araldite B by high-speed holographic microscopy

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Abstract

High-speed holographic microscopy is applied to take three successive photographs of fast propagating cracks in Homalite 100 or in Araldite B at the moment of bifurcation. Crack speed at bifurcation is about 540 m/s on Homalite 100, and about 450 m/s on Araldite B. From the photographs, crack speeds immediately before and after bifurcation are obtained, and it is found that discontinuous change of crack speed does not exist at the moment of bifurcation in the case of Homalite 100, but exists in the case of Araldite B. From the photographs, crack opening displacement (COD) is also measured along the cracks as a function of distance r from the crack tips. The measurement results show that the CODs are proportional to $\sqrt{r}$ before bifurcation. After bifurcation, the CODs of mother cracks are proportional to $\sqrt{r}$, though the CODs of branch cracks are not always proportional to $\sqrt{r}$. The energy release rate is obtained from the measured CODs, and it is found that energy release rate is continuous at bifurcation point in both cases of Homalite 100 and Araldite B. Energy flux that shows the energy flow toward a crack tip is also obtained.

Keywords: Crack branching and bifurcation; Dynamic fracture; Energy release rate; Stress intensity factor; Holography

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1. Introduction

When brittle materials break under external force, there appear fast propagating cracks that are of opening mode and whose speed is from 200 to 2000 m/s. When the crack speed is high enough, a fast propagating crack bifurcates into two cracks suddenly. Bifurcation is a characteristic feature of fast propagating cracks, accordingly, many researchers have studied it theoretically (Yoffe, 1951; Baker, 1962; Congleton and Petch, 1967; Theocaris and Georgiadis, 1985), experimentally (Dally, 1979; Aoki and Sakata, 1974, 1980; Ramulu and Kobayashi, 1985; Ravi-Chandar and Knauss, 1984; Arakawa and Takahashi, 1991; Sharon and Fineberg, 1999; Suzuki et al., 2000; Suzuki and Sakaue, 2004; Livne et al., 2005) and numerically (Seelig and Gross, 1999; Nishioka et al, 2001). But the mechanism of the rapid crack bifurcation has not been fully understood.

One of the important problems to figure out the bifurcation mechanism is the continuity of energy release rate at bifurcation. After bifurcation, the area of the crack surfaces that are newly made by the crack extension of unit length is twice as large as that before bifurcation. Consequently, if the crack speed after bifurcation is the same as that before bifurcation, the energy release rate of the crack after bifurcation must be twice as large as that before bifurcation. On the other hand, if the energy release rate after bifurcation is the same as that before bifurcation, crack speed after bifurcation is expected to be smaller than that before bifurcation. In order to understand the mechanism of rapid crack bifurcation it is important to make clear whether the discontinuous increase of energy release rate or discontinuous decrease of crack speed really occurs or not.

Crack speeds just before and after bifurcation have been measured with high-speed cameras by some researchers. Dally (1979) and Ramulu and Kobayashi (1985) reported that the decrease of crack speed immediately after bifurcation is less than 10% of the crack speed before bifurcation. Ravi-Chandar and Knauss (1984) measured the crack speed with the caustic method, and observed no change of crack speed at bifurcation.

Fineberg et al. (1992) applied the method of the resistance change of a thin aluminum layer evaporated on a specimen surface to measure crack speed. Their method has temporal resolution much higher than high-speed cameras, and found the fluctuation of the crack speed of about 600 kHz. The fluctuation is thought to be caused by the appearance of micro-branching (Sharon and Fineberg, 1996); however, it is an open problem whether or not the micro-branching is the same as the macroscopic crack bifurcation.

On the other hand, energy release rate before bifurcation has so far been measured with optical methods, for example, photoelasticity (Kobayashi et al., 1974; Irwin et al., 1979; Dally, 1979), caustic method (Ravi-Chandar and Knauss, 1984; Kalthoff, 1987; Arakawa and Takahashi, 1991) and holographic microscopy (Suzuki et al., 1988; Suzuki et al., 1997). But the energy release rate immediately after bifurcation has not been measured because of difficulties on measurement. Since the distance between the two tips of the crack branches is very small just after bifurcation, strong interaction occurs between them. Hence, there has been no method to measure accurately the energy release rate immediately after bifurcation (Kobayashi et al., 1974; Ramulu and Kobayashi, 1985). In order to answer the question on the (dis)continuity of energy release rate at bifurcation, it is necessary to measure the energy release rate both before and after bifurcation.

Recently, Suzuki and Sakaue (2004) applied high-speed holographic microscopy to measure the energy release rate of fast propagating cracks in PMMA within 10 μs before