**TECHNIQUES** *2001 SEM Student Paper Competition Winner—2nd Place*
*by L.R. Xu and A.J. Rosakis*

# REAL-TIME EXPERIMENTAL INVESTIGATION OF DYNAMIC CRACK BRANCHING USING HIGH-SPEED OPTICAL DIAGNOSTICS

Dynamic crack branching is an important dynamic failure mode for brittle materials and for ductile materials subjected to certain conditions. This phenomenon has received extensive attention in the past decades. However, previous major efforts have primarily focused on analytical and numerical studies.[1–8] Very few experimental results were available to verify predictions or to provide guidance for modeling.[9–13] Some important issues, such as the crack speed change before and after branching, effect of dynamic loading rate on crack branching, and crack branching induced by stress wave loading are still open. Indeed, in this investigation, we concentrate on all of the above-mentioned phenomena and focus on how to realize various forms of dynamic crack branching under a variety of conditions. The objectives are to elucidate a series of new phenomena; and to provide guidance for developing theoretical models and validating numerical simulations.

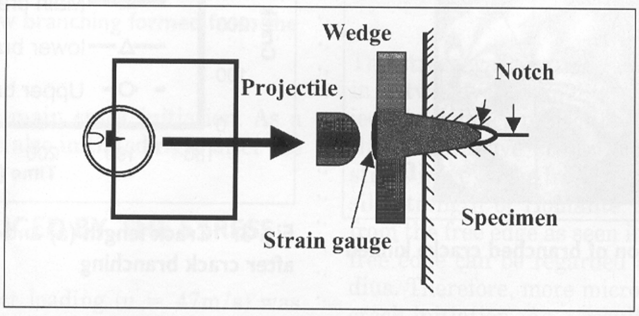

**Fig. 1: Illustration of a novel wedge-notch design to produce a mode I crack during projectile impact**

## MATERIALS AND SPECIMENS

Two kinds of polymeric materials were used in conjunction with two kinds of optical diagnostic techniques. Homalite–100 was chosen for the photoelasticity experiments while PMMA was used in the Coherent Gradient Sensing (CGS) experiments.[14] Various types of specimens were designed and some of them had pre-notches with different radii. One major specimen used in this investigation was a novel wedge-loaded specimen, which was designed to produce a single, straight dynamic crack as shown in Fig. 1. An aluminum wedge was inserted into a pre-notch and impacted by a projectile, causing the wedge to open the notch faces thus producing a single mode I crack. The notch tip was cut using a diamond wafering blade (Buehler, Series 15 LC). A strain gauge was bonded onto the wedge to trigger the high-speed camera and laser system.

## TWO KINDS OF HIGH-SPEED OPTICAL DIAGNOSTICS

Dynamic photoelasticity was used in most of the experiments. This method is sensitive to the maximum in-plane shear stresses encountered in the specimen during the loading and failure process. The CGS technique records the gradient of the first in-plane stress invariant. A projectile fired from a gas gun was used to apply the impact loading through the wedge to initiate the crack. A high-speed camera was employed to record the fringe patterns in real time. More experimental details can be found in reference 15.

## CRACK KINKING AND BRANCHING FROM AN INTERFACE

As shown in Figure 2, the in-plane Homalite specimen dimensions were 457 mm long, 254 mm wide and the plate thickness was 9.5 mm. In this photoelasticity experiment, the initial notch radius was 0.127 mm (0.005″). For a low impact speed, $V = 19$ m/s, only a pure mode I crack initiated from the notch. As seen in Fig. 2(b), we created an artificial interface (an inclined thin line) in front of the horizontally propagating crack. The incident mode I crack approached the interface at about 151 μs after impact and transitioned into a mixed-mode interfacial crack. A vertical line appearing in every image is the camera streak line, which was used for positioning and reference purposes. The dark circular spot at the center of every photo is a scaling mark of 6.35 mm in diameter. At approximately 177 μs, this mixed-mode interfacial crack kinked into the right side of the interface. A significant caustics (or shadow spot) is seen in Fig. 2(d) to show the mode I nature of the kinked crack. The speed of the kinked crack was high enough to induce multiple branches, which are visible in Figs. 2(e) and (f). A similar branching phenomenon was found in our recent experiments of impact failure of layered materials.[16] Crack length and speed records of the main crack and the branched cracks are presented in Fig. 3. Differentiation of the crack length record furnishes the tangential crack tip speed before and after crack branching. Since the differentiation process is based on a three-point-fitting procedure of the crack length history, the exact crack speed at the crack branching could not be obtained. It is interesting to notice that the main crack tip speed is almost equal to the branched crack tip speed under the current time resolution (2.6 μs per frame). Ravi-Chandar also obtained a similar result.[17] The crack branching speed was about 28% of the shear wave speed of Homalite subjected to the high strain rate.[16]

## CRACK BRANCHING INITIATED FROM A NOTCH SUBJECTED TO HIGH IMPACT LOADING

If we kept all other conditions from the previous case but raised the impact speed to 30 m/s (58% increase), a mode I

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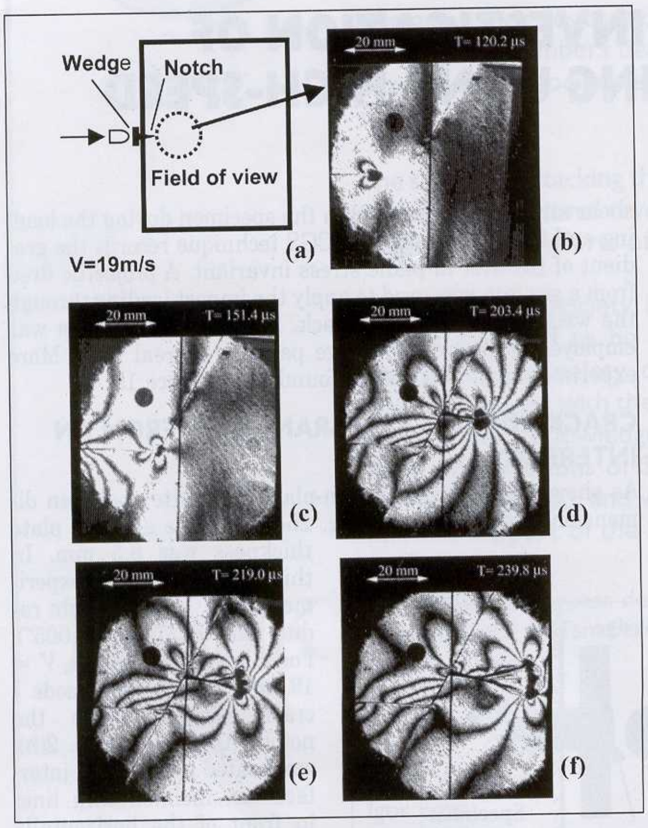

**Fig. 2: Formation and propagation of branched cracks kinked from an interfacial crack**

crack was observed at first as shown in Fig. 4(b). However, this main crack soon branched into two cracks as seen in Fig. 4(c). At a later time, one branched crack (upper branch) generated two new sub-branching cracks as shown in Fig. 4 (d). Previous experiments reported that the branching angle was less than 45 degrees.[7,10] However, in our experiment, the first branching angle is around 45 degrees and the second branching angle is about 67 degrees, which is approximately the theoretical branching angle (60 degrees) first reported by Yoffe.[1] The mechanism of crack branching subjected to a high loading (impact) rate can be explained by the dynamic energy release rate (driving force).[18] The availability of kinetic energy due to high impact speed tends to create more fracture surfaces for absorbing energy. Therefore, branched cracks easily occur in a high impact loading case.

## CRACK BRANCHING INITIATED FROM THE NOTCH WITH A LARGE RADIUS

Dynamic crack branching is related to the initial notch radius. In this test, we kept other conditions from the previous case but increased the notch radius to 0.222 mm (0.00875″). Cracks soon branched from the notch tip right after impact and formed a curved pattern as shown in Fig. 5(b) and (c). The central branched crack kept branching into more cracks as seen in Fig. 5(d). It was observed that the branching angle was 55 degrees, which is very close to the theoretical branching angle 60 degrees again. Later on, the different stress wave patterns were observed across the branched interface due to possible friction at the interface. The curved branching shape might be a validation example for numerical simulations. In terms of the crack branching mechanism for a large notch radius, micro-crack formation is a possible major factor. According to previous research results,[12] crack branching is caused by the formation of a micro-crack in front of a main crack. Because of the large notch radius, the strain energy may accumulate to a very high level to induce

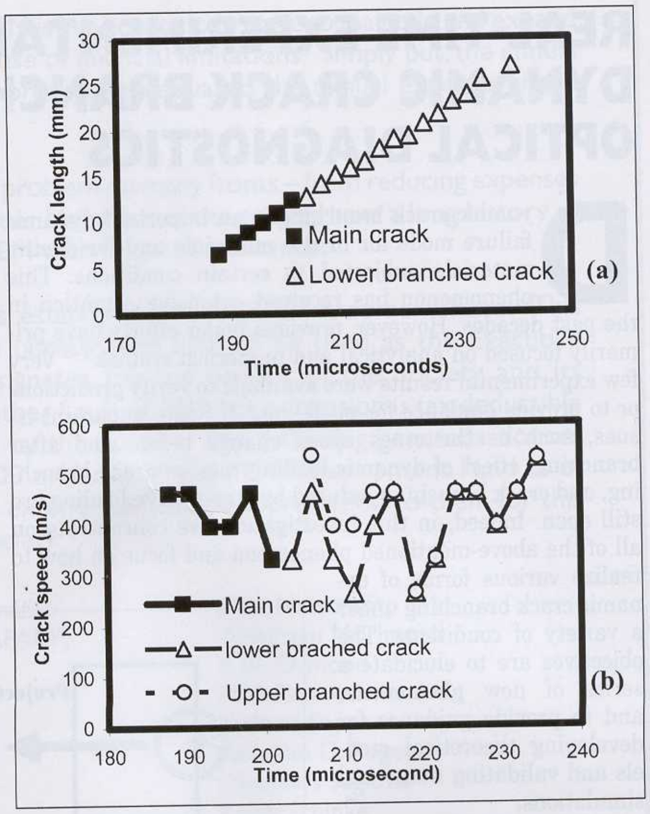

**Fig. 3: Crack length (a) and speed (b) variations before and after crack branching**

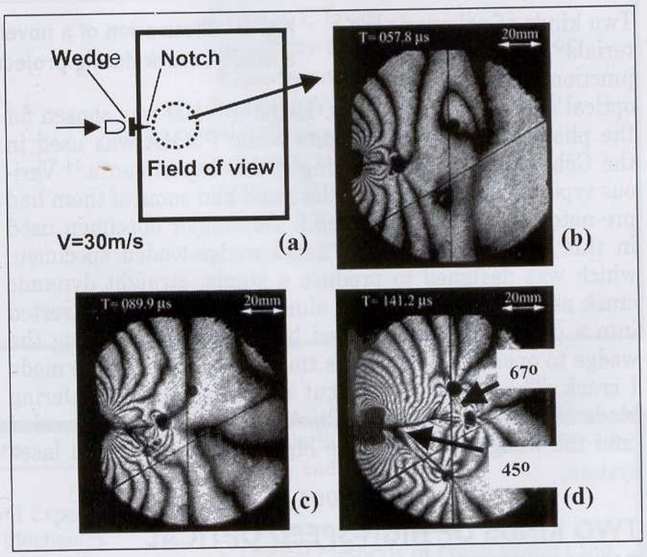

**Fig. 4: Crack branching after a mode I crack initiation if the notch radius was small but impact loading was high**

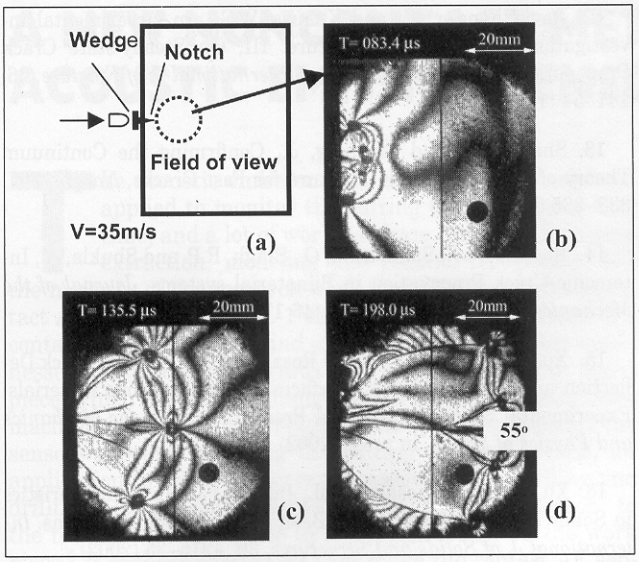

**Fig. 5: Three branched cracks initiated from the notch with a large radius (b and c) and a new branching formed from the central crack (d)**

several microcracks before the main crack initiation. As a result, several branching cracks also initiated right after the main crack propagated.

## CRACK BRANCHING INDUCED BY THE STRESS WAVE

In this CGS test, a high impact loading ($v = 47\text{m/s}$) was applied to a PMMA plate ($406 \times 241 \times 6\ \text{mm}^3$) as shown in Fig. 6. A pure mode I crack initiated from the notch at first. Then, because the reflected tensile stress wave from the free boundary entered the crack propagation area and formed a complicated stress wave interaction, this main mode I crack was arrested and two other branched cracks formed in Fig. 6 (c). These two branched cracks continued to propagate and left the field of view. After a long time period, the main mode I crack started to propagate towards the upper free edge again.

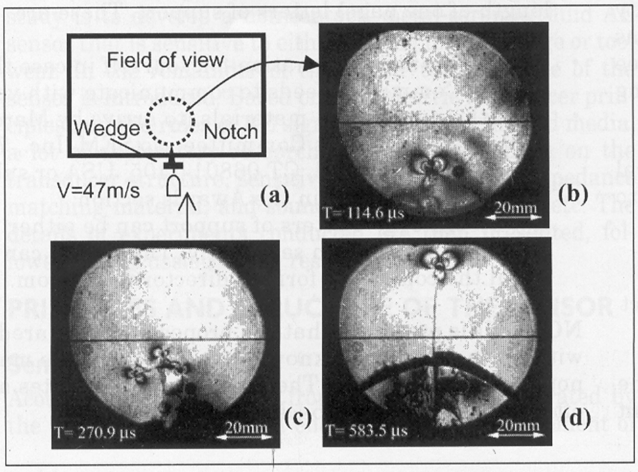

**Fig. 6: CGS pictures of dynamic crack propagation, arrest and branching induced by the reflected stress wave**

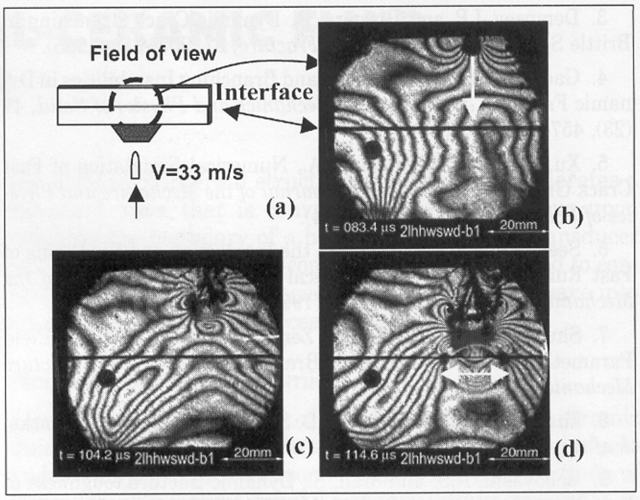

**Fig. 7: A group of branched cracks approached the interface (thin dark line) and induced an interfacial crack of a two-layer Homalite specimen**

The stress wave-induced crack branching was also observed in a two-layer Homalite specimen with a weak bond subjected to direct projectile impact as shown in Fig. 7. After the compressive stress wave transitioned into the tensile stress wave at the free edge, its magnitude exceeded the tensile strength of Homalite. Hence, a mode I crack initiated from the free edge as seen in Fig. 7 (b). However, the straight free edge can be regarded as a notch with a very large radius. Therefore, more microcracks will form before the main crack initiation. As a result, as soon as the main crack initiated, it branched into several cracks. It is interesting to observe that the interfacial crack was induced before these branched cracks approached the interface. This is direct evidence of the dynamic equivalent of the Cook-Gordon mechanism of brittle interfacial fracture.[15]

## CONCLUDING REMARKS

1. The speed of the branched crack is almost equal to the speed of the main crack.
2. The crack branching angle can be larger than 45 degrees for brittle polymers.
3. A stress wave may induce complicated crack branching.
4. Crack branching easily occurs if the initial notch radius is large or the loading rate is high.

## ACKNOWLEDGMENTS

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- Prepare a summary of those of the nominee's outstanding accomplishments that are relevant to the award in question. This should not be an employment history.
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- Provide information about the nominee's other notable professional achievements, if appropriate. Include information about the nominee's publications and/or patents if appropriate for the award in question.
- Obtain and attach two or three short (maximum length of one page) letters of support. These are required.
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