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# FURTHER STUDIES ON DYNAMIC CRACK CURVING

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by

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# FURTHER STUDIES ON DYNAMIC CRACK CURVING

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The elasto-dynamic stress field surrounding rapidly propagating cracks in thin polycarbonate, double edged crack tension specimens were analyzed by dynamic photoelasticity using a 16-spark gap Cranz-Schardin camera system. Crack curving was observed in two slanted double edged crack specimens and in two offset parallel double edged crack specimens. In another test, the crack ran straight between two symmetrically located twin cracks. Results of these five tests were used to verify the dynamic crack curving criterion by Ramulu et al. in which a reference distance of

ro=1/128/pi*[K1/sigmaox*V(c,c1,c2)]** 2

from the crack tip is incorporated into the maximum circumferential stress or minimum strain energy density criteria. The critical material property for crack curving in this thin polycarbonate sheet was found to be about rc= 0.5 mm.

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## INTRODUCTION

In a paper in 1963, Erdogan and Sih [1] used the orientation of maximum circumferential stress to predict crack extension of inclined cracks in tension specimens. This mixed mode crack extension criterion, commonly referred to as the maximum circumferential stress criterion, was later advanced among others by Williams and Ewing [2] and Finnie and Saith [3]. More recently, Streit and Finnie [4] incorporated the second order term, sigmaox, in the crack tip stress field and proposed a crack curving criterion based on the directional stability of a mode I crack propagation. This stability criterion introduced another critical material parameter, ro, which is the radial distance from the crack tip. The second order term of sigmaox was also used by Cotterell and Rice [5] for predicting the crack curving direction of a slightly curved crack. Historically, Yoffe was the first to use the maximum circumferential stress theory to explain surface roughening and crack branching of a rapidly propagating crack in 1951 [6].

As a natural extension of Griffith's energy release rate, Hussain et al. [7], Palaniswamy and Knauss [8] among others predicted the direction of crack kinking based on the maximum energy release criterion. Focusing directly on energy, Sih [9] predicted that the crack would kink in the direction of the minimum strain energy density factor, S. In an early critique of 1976, Swedlow [10] concluded that the difference between the crack kinking angle predicted by the maximum circumferential stress criterion and the minimum strain energy density criterion "are modest at most". Theocaris and Andrianopolous [11] recently modified the S theory and designated the mean value of $\bar{S}$, a critical material value for crack extension. Sih [12] also applied the minimum S theory to predict crack kinking of a dynamic crack.

Ramulu et al., in a recent paper [13], incorporated the second order term of sigmaox in the dynamic crack tip stress field and then derived the dynamic counterpart of the crack stability model based on the maximum circumferential stress criterion as well as the minimum strain energy density factor. This dynamic crack curving criterion was used to evaluate nine dynamic photoelasticity tests involving curved as well as straight propagating cracks in fracturing Homalite-100 specimens. The critical material property of rc was found to be 1.3 mm for the Homalite-100 specimens investigated. More importantly, the crack curving directions predicted by either the maximum circumferential stress theory or the minimum strain energy density theory were generally within 1 degree of each other for the relatively low crack velocities observed in these tests. The sign of sigmaox was also found to influence significantly the crack angle of a running crack. The purpose of this paper is to provide further evidence in support of the dynamic crack curving criterion advanced by Ramulu et al.

## DYNAMIC CRACK CURVING CRITERIA

### Maximum Circumferential Stress Criterion

The maximum circumferential stress criterion, as modified by Ramulu et al. [13], assumes that the crack will extend towards the maximum circumferential stress which reached its critical value at a critical distance, rc, away from the rapidly propagating crack tip. rc is a characteristic distance derivable from the crack stability criterion

involving the second order term of sigmaox in the dynamic crack tip stress field. This characteristic distance is [13].

$$ro = 1/128/pi*[KI/sigmaox*V(c,c1,c2)]**2$$

where KI is the dynamic stress intensity factor.

sigmaox is the second order term in the dynamic stress field and is often referred to as the remote stress component.

c, c1 and c2 are the crack velocity, dilatational wave velocity and the shear wave velocity, respectively.

V(c,c1,c2) is the dynamic correction factor to the static crack instability criterion and is given in Reference [13].

This crack curving criterion which is the dynamic extension of that by Streit and Finnie [3] can be used to predict the crack curving of a crack propagating under pure mode I as well as mixed mode, i.e. modes I and II, conditions.

### Minimum Strain Energy Density Criterion

The minimum strain energy density criterion, as modified by Ramulu et al. [13], also incorporates the characteristic distance of ro and thus the second order term of sigmaox in the strain energy density factor, S, of Sih [9]. Unlike the maximum circumferential stress criterion, the minimum S condition yields a relation between the crack curving angle and ro in terms of the given sigmaox and modes I and II stress intensity factors, KI and KII. Given ro, however, the extended minimum strain enrgy density criterion with the sigmaox term can be used to predict crack curving of a mode I static crack or a crack propagating at a low crack velocity.

### Homalite-100 Fracture Specimens

The validity of the above two dynamic crack curving criteria were assessed through re-evaluated dynamic photoelasticity results of Homalite-100 fracture specimens [14-18]. ro for the minimum S criterion was equated to rc which was found to be about 1.3 mm for the Homalite-100 data used in evaluating the maximum circumferential stress criterion. For the relatively low crack curving angles of -20 to 25 degrees observed in the nine tests, both the maximum circumferential stress and the minimum strain energy density criteria predicted the fracture angles within 1 degree for most of the 81 data points considered in this investigation [13].

## POLYCARBONATE FRACTURE SPECIMENS

In order to further verify the above dynamic crack curving criteria, a series of dynamic photoelastic fracture experiments involving thin polycarbonate fracture experiments were conducted. Specimen configurations and the crack paths in five double edged crack tension specimens with either offset parallel cracks offset slanted cracks and symmetrically located twin cracks, used in this investigation are shown in Figure 1. The annealed thin polycarbonate specimens with blunt starter cracks exhibited brittle fracture with shear lips less than 10 percent of the thickness and an apparent crack tip yield zone of less than 1.5 mm. The dynamic isochromatics surrounding the propagating crack were recorded with a 16 spark gap Cranz-Schardin camera system.

The isochromatic data were reduced by least square fitting to the recorded dynamic isochromatics a theoretical mixed-mode, dynamic crack tip stress field with disposable parameters of KI, KII and sigmaox [19]. The characteristic crack tip distance, ro, was then computed by Equation (1). With ro known, the predicted crack curving angle can be computed by the maximizing condition for the maxmimum circumferential stress criterion or the minimizing condition for the minimum S criterion. Details of this data reduction procedure can be found in Reference [20].

## RESULTS

As shown in Figure 1, crack always propagated from the longer left crack and curved towards the shorter stationary right crack except for Specimen S2-810518 which involved a symmetrically located twin crack. Also the eccentric loading of Specimens S15-810727 and the longer initial crack length of Specimen S5-810530 caused the rapidly propagating upper crack to intersect with the stationary lower crack at its midcrack length.

Figure 2 shows two typical dynamic isochromatic patterns in a fracturing offset, slanted, double edged crack tension specimen. The right edge crack did not propagate during the entire fracture event. Both frames in Figure 2 show the expanding shear wave front which emanated from the original crack tip of the left edged crack when it started to propagate. Figure 3 shows the variations in KI, KII, sigmaox and crack velocity of the upper crack in Figure 2. While the crack velocity and KI remained essentially constant through the relatively straight propagation of the upper crack, sigmaox oscillated consistent with previous observations [13].

Figure 4 shows two typical dynamic isochromatic patterns in a fracturing offset, parallel double edged crack specimen. Although the upper crack had cut the specimen in half, the stationary lower crack continued to show a high mode II crack tip stress field in Frame No. 10 of this figure. A similar high mode II crack tip stress field was observed in all stationary cracks during the latter part of crack propagation history. Figure 5 shows the variations in KI, KII, sigmaox and crack velocity of the upper crack in Figure 4. The larger excursion in KI in this figure is associated with the curved crack shown in Figure 4. Figure 6 shows the KI, KII and sigmaox of the lower stationary crack in Figure 4. While KI=3, Mpa$\sqrt{m}$, of this crack was close to the estimated fracture toughness of polycarbonate, the small difference in the crack tip bluntness probably prevented crack propagation of the lower right crack. KII of the stationary crack varied from -8.5 to 0.6 MPa$\sqrt{m}$. and is about half of the KI value. This high value, not commonly observed in previous dynamic photoelastic experiments, is due to the load redistribution caused by the decreasing remaining ligament in the fracturing specimen.

Figure 7 shows typical isochromatics of an edge crack propagating between two symmetrically located twin cracks. High mode II crack tip stress fields are noted in the stationary twin cracks in Frame No. 12 of this figure. Figure 8 shows the variations in KI, KII, sigmaox and crack velocity of the propagating left crack. Oscillations in sigmaox are smaller in this straight crack which is propagating at approximately the same crack velocity of 0.2*cl as the other cracks.

Figure 9 shows the variations in characteristic distance, ro, which was computed by Equation (1), for the propagating cracks in the the five tests. ro for the curved portion of the rapidly propagating crack is larger than the ro of the straight crack. Also ro, within the scatter band indicated in Figure 9, always dropped to a minimum value at the onset of crack curving. The

scatter band of the minimum value of ro yield an average rc=0.5 mm. This value is consistent with the rc value estimated by Theocaris [21].

Having estimated the rc for this thin polycarbonate fracture specimens, the crack curving angle was then estimated either by using the maximum circumferential stress or the minimum S criteria. The results, as summarized in Table 1, show that the predicted and experimentally observed crack curving angles for these five tests were mostly within 1 degree of each other regardless of the crack curving criterion used.

## CONCLUSIONS

1. Dynamic crack curving angle under pure mode I and mixed mode I and II conditions can be predicted by using either the extended maximum circumferential stress or the minimum strain energy density criteria.

2. The critical characteristic crack tip distance is rc=0.5 mm for the thin polycarbonate fracture specimens considered in this investigation.


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TABLE 1

SUMMARY OF EXPERIMENTAL AND THEORETICAL RESULTS

| | |
|---|---|
| Total Number of Experiments: | 5 |
| Type of Fracture Specimens: | Double Edged Crack Specimen |
| Number of Data Points: | 114 |
| Crack Velocity, c/cl: | About 0.2 |
| KI ($MPa\sqrt{m}$): | 1.5 to 3.2 |
| KII ($MPa\sqrt{m}$): | -0.5 to 0.6 |
| sigmaox/KI: | -11.1 to 2.5 |
| ro (mm): | 0.25 to 0.75 |
| Measured Crack Curving Angle: | -20 to 3 degrees |
| Predicted Crack Curving Angle: | |
| Maximum Circumferential Stress: | -19 to 5 degrees |
| Minimum S: | -18 to 5 degrees |

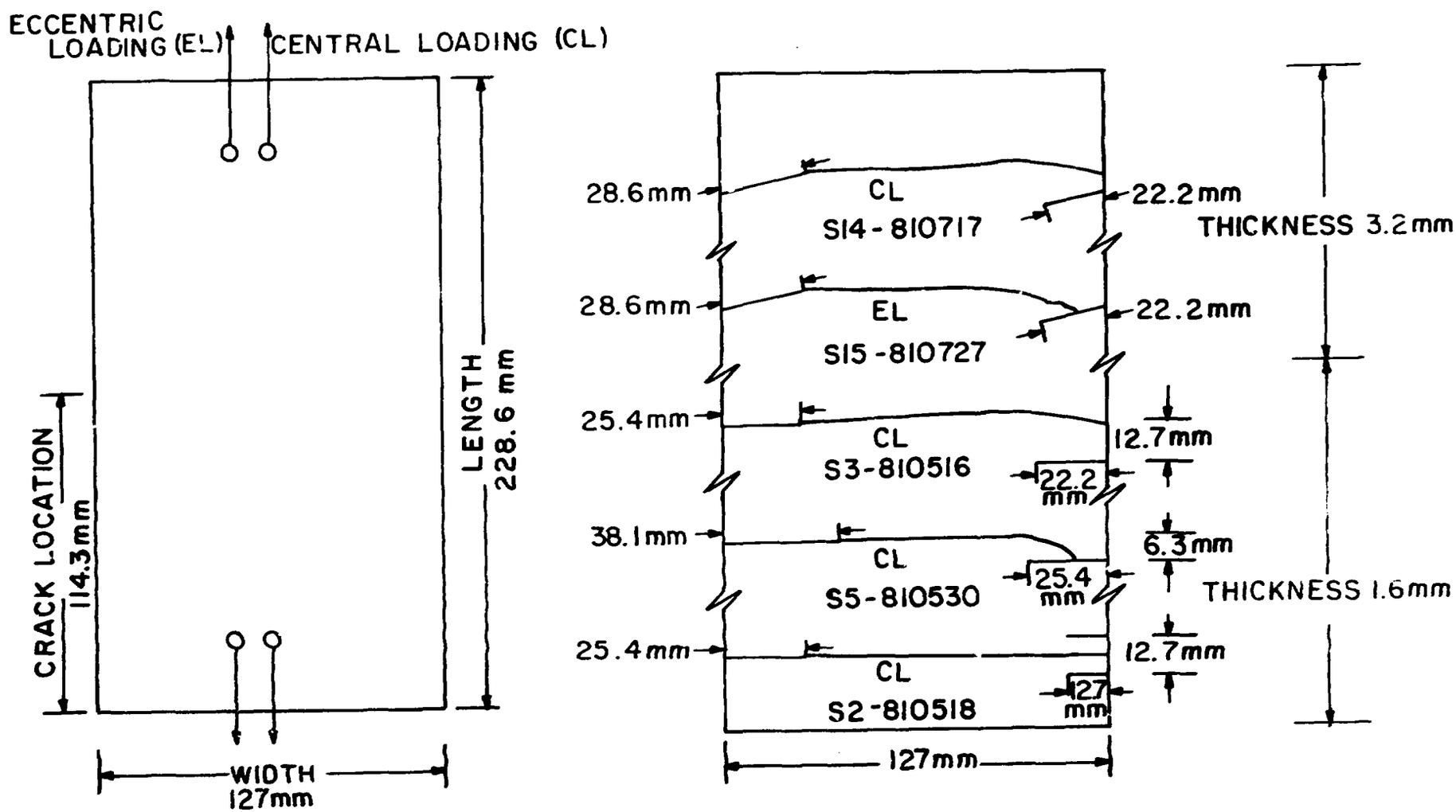
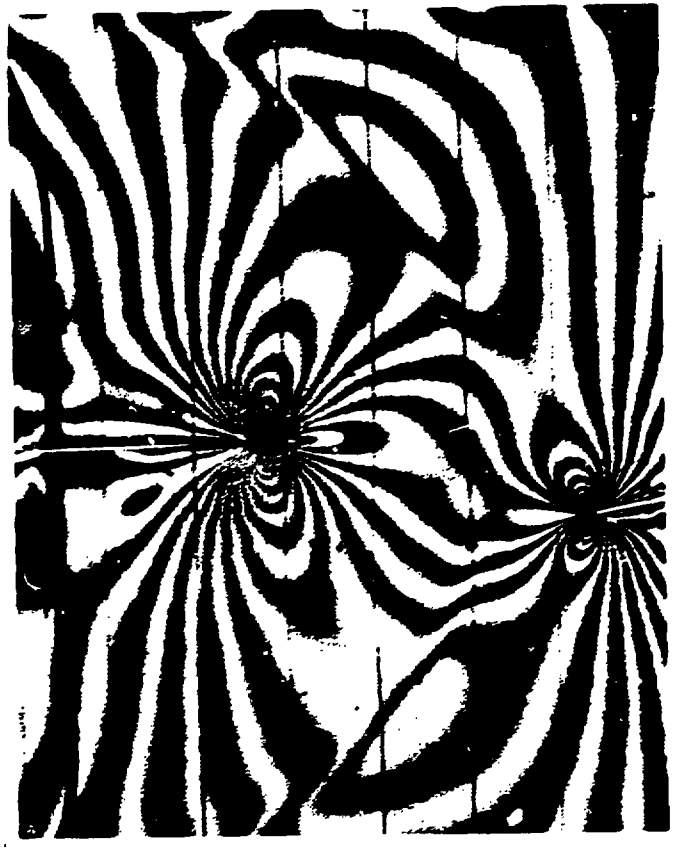



FIG. 1. POLYCARBONATE DOUBLE EDGED CRACK TENSION SPECIMEN.

FIRST FRAME
6 $\mu$ SECONDS



SEVENTH FRAME
28 $\mu$ SECONDS

FIG. 2. TYPICAL DYNAMIC PHOTOELASTIC PATTERNS IN POLYCARBONATE SLANTED DOUBLE EDGED CRACK TENSION SPECIMEN. SPECIMEN NO. S14-810717.

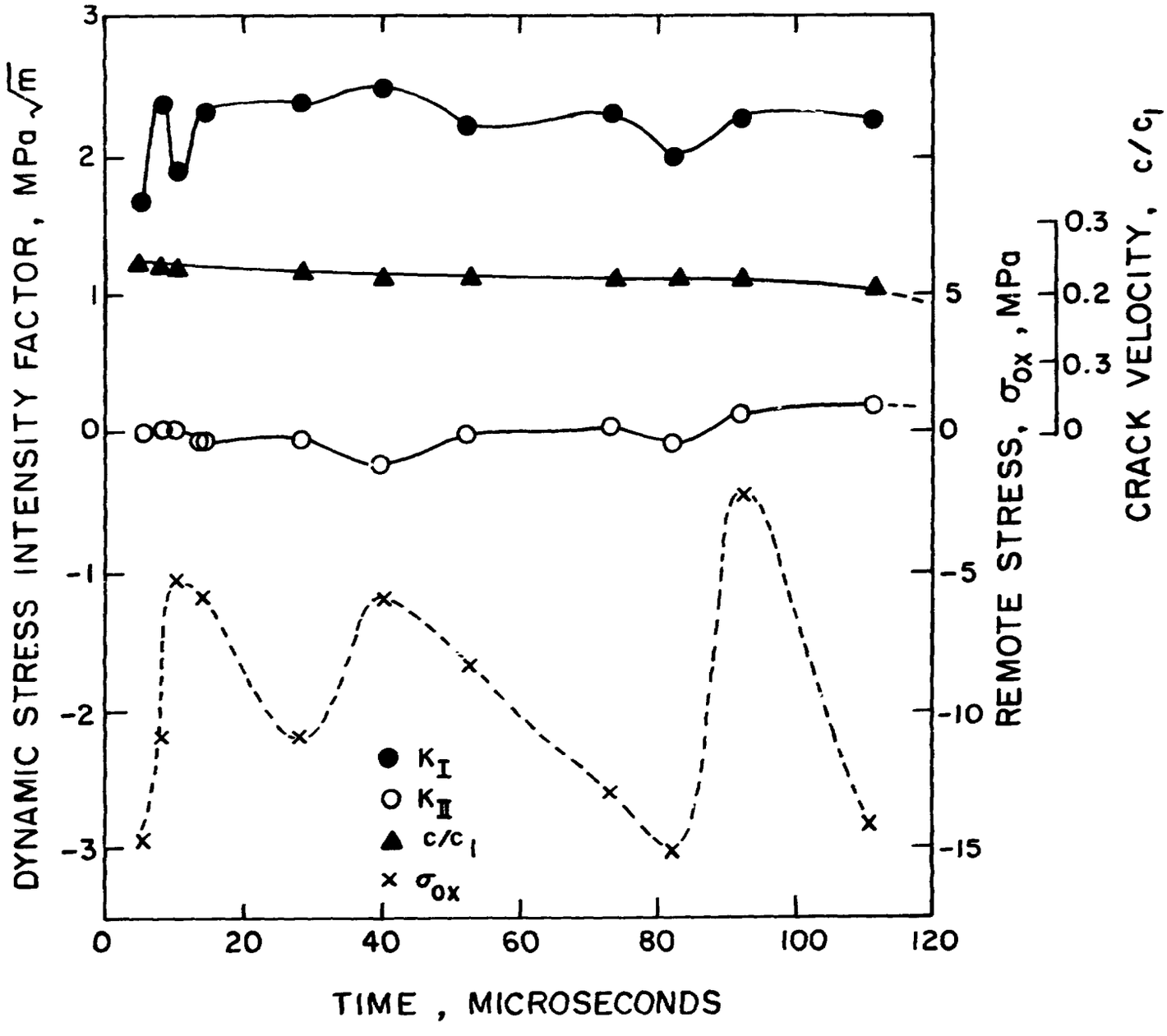



FIG. 3. DYNAMIC STRESS INTENSITY FACTOR, CRACK VELOCITY AND $\sigma_{0x}$ OF UPPER CRACK OF SPECIMEN NO. S14-810717.

SEVENTH FRAME
150 $\mu$ SECONDS

TENTH FRAME
225 $\mu$ SECONDS

FIG. 4. TYPICAL DYNAMIC ISOCHROMATICS OF A CURVED CRACK IN A POLYCARBONATE PARALLEL DOUBLE EDGED OFFSET CRACK TENSION SPECIMEN. SPECIMEN NO. S3-810526.

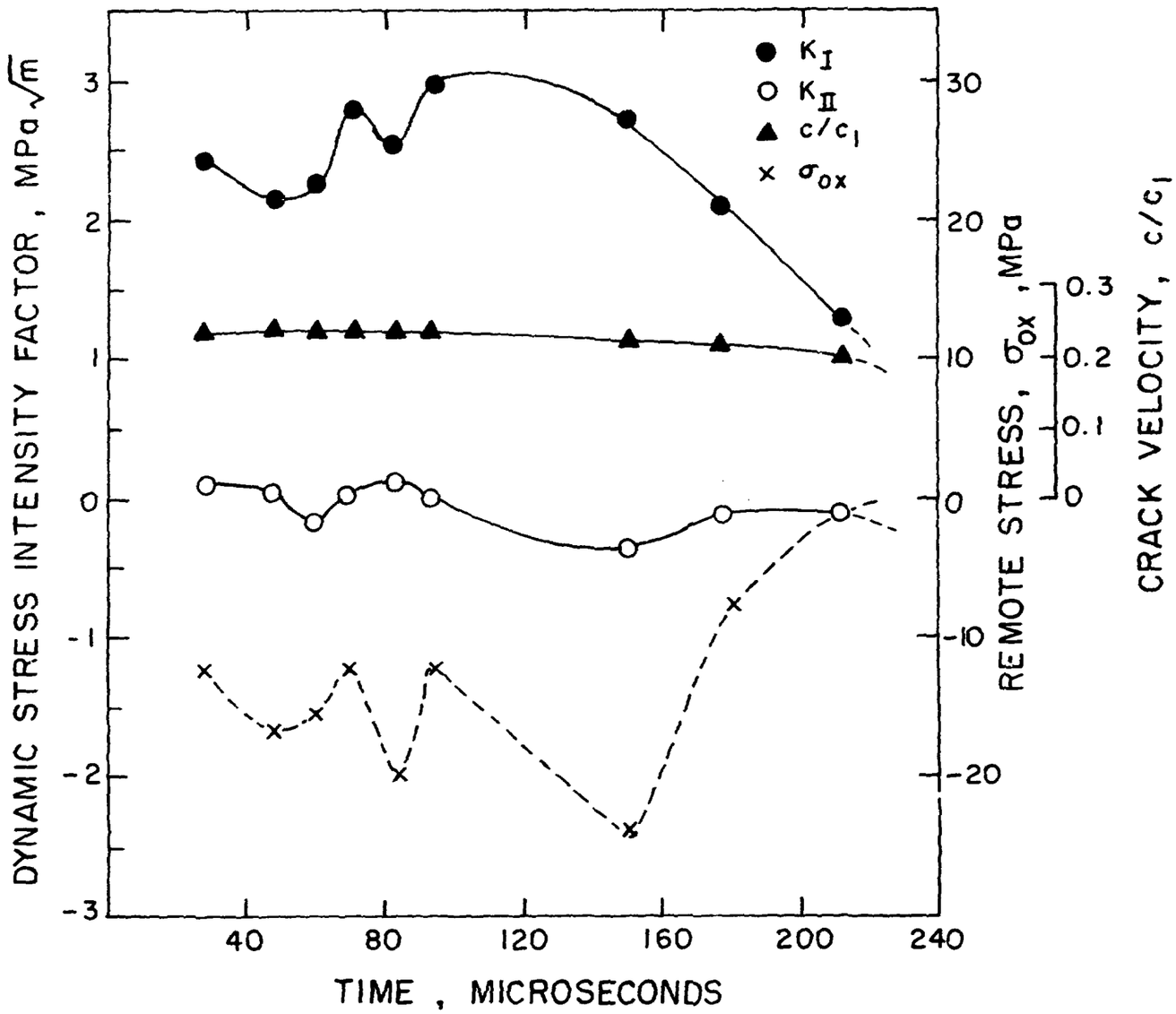



FIG. 5. DYNAMIC STRESS INTENSITY FACTOR CRACK VELOCITY AND $\sigma_{ox}$ OF UPPER CRACK OF SPECIMEN NO. S3-810526.

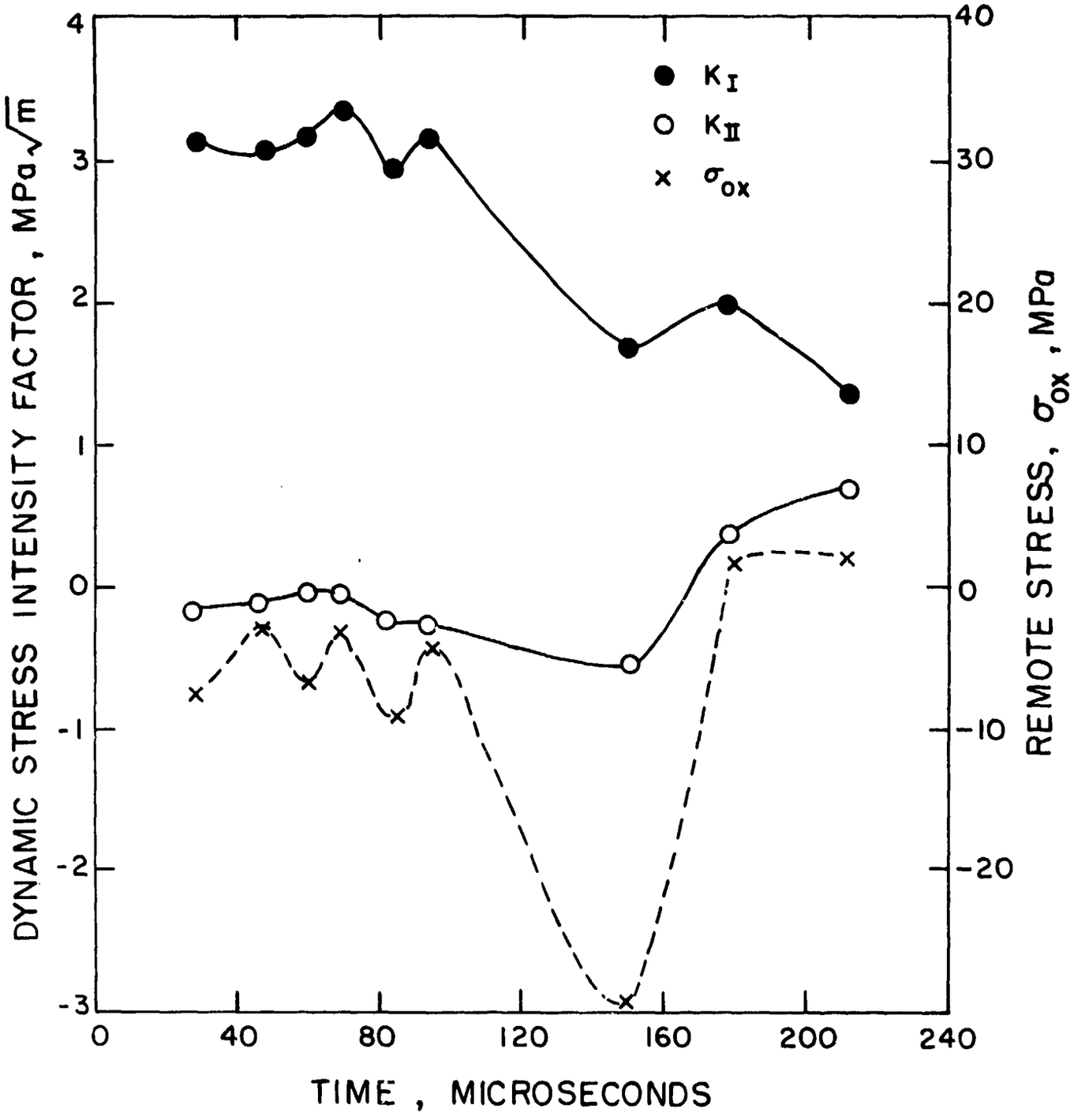
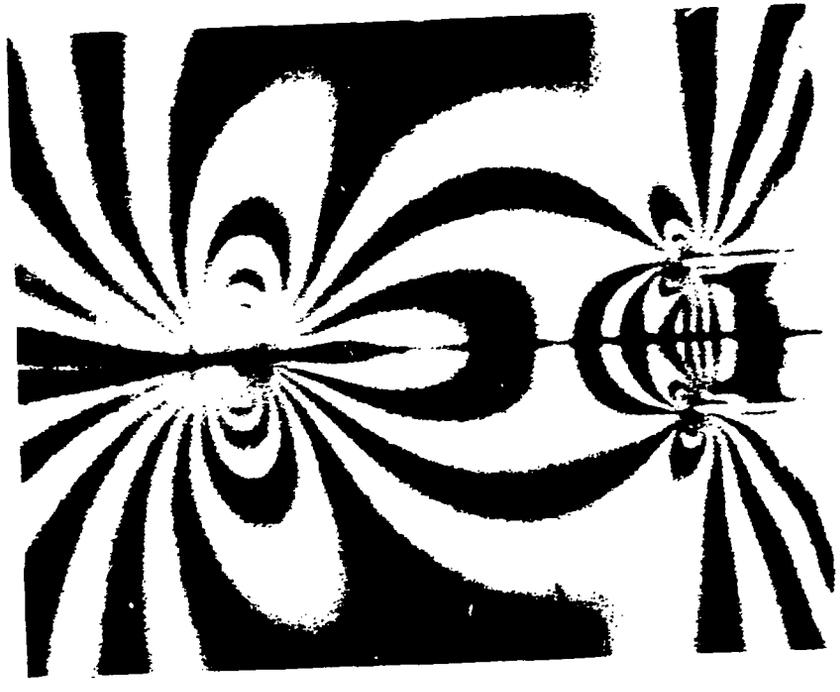
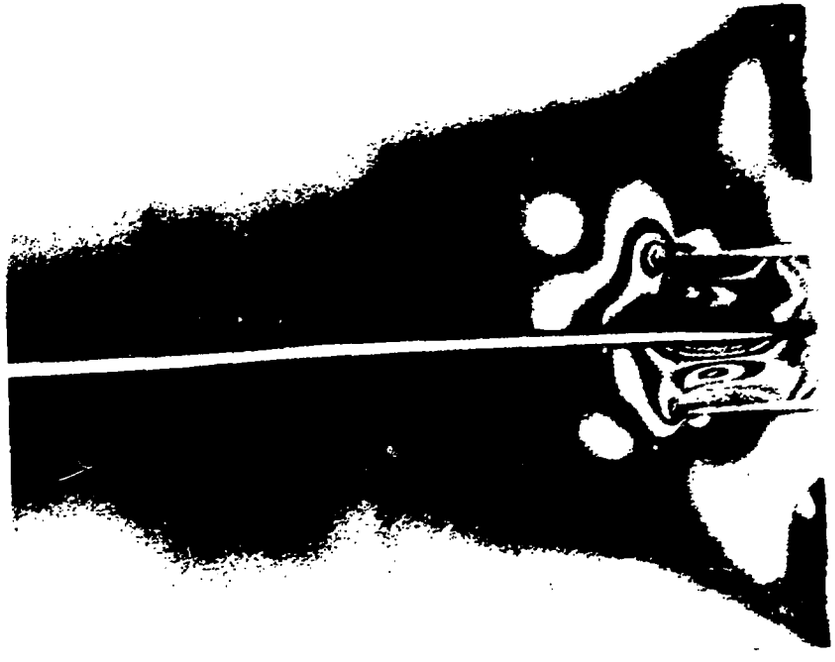



FIG. 6. DYNAMIC STRESS INTENSITY FACTOR AND $\sigma_{ox}$ OF THE STATIONARY LOWER CRACK OF SPECIMEN NO. S3-810526.



SIXTH FRAME

100 $\mu$ SECONDS



TWELFTH FRAME

262 $\mu$ SECONDS

FIG. 7. TYPICAL DYNAMIC ISOCHROMATICS OF A STRAIGHT CRACK PASSING THROUGH SYMMETRICALLY LOCATED TWIN CRACKS. SPECIMEN NO. S2-810518.

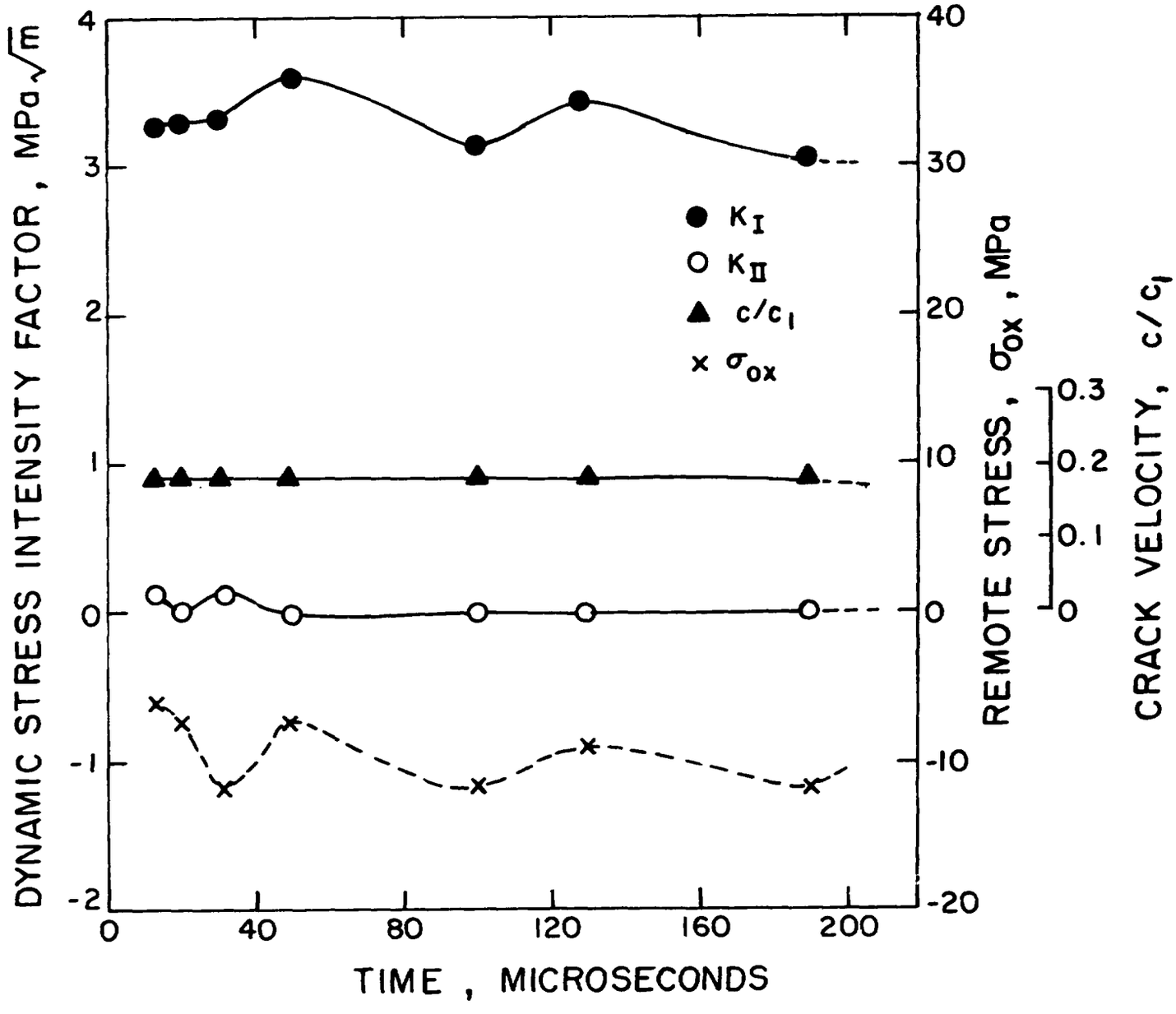



FIG. 8. DYNAMIC STRESS INTENSITY FACTORS, CRACK VELOCITY AND $\sigma_{ox}$ OF THE RUNNING CRACK OF SPECIMEN NO. S2-810518.

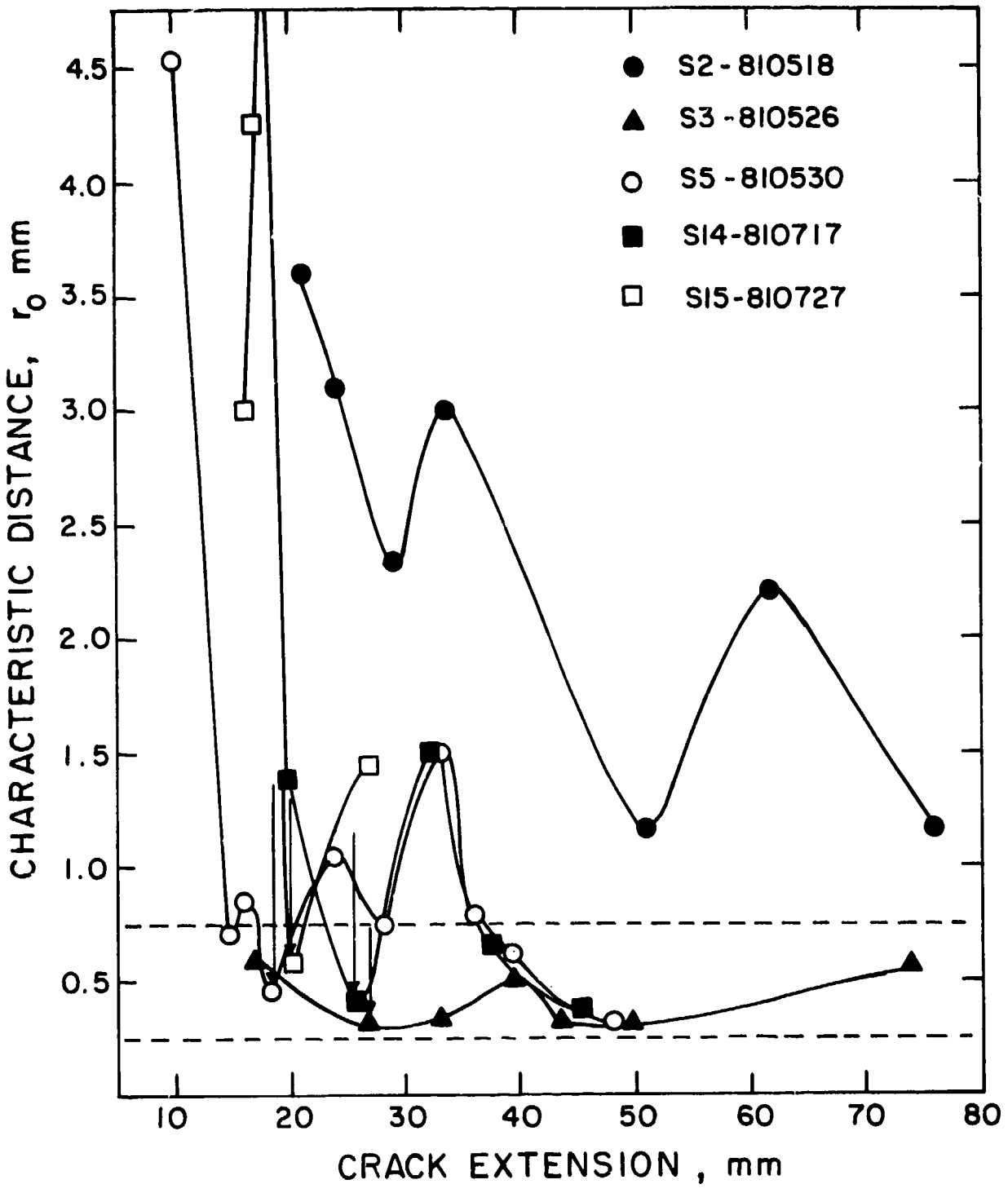



FIG.9. CHARACTERISTIC DISTANCE $r_0$ OF PROPAGATING CRACK IN THE POLYCARBONATE DOUBLE EDGED CRACK TENSION SPECIMENS.

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The elasto-dynamic stress field surrounding rapidly propagating cracks in thin polycarbonate, double edged crack tension specimens were analyzed by dynamic photoelasticity using a 16-spark gap Cranz-Schardin camera system. Crack curving was observed in two slanted double edged crack specimens and in two offset parallel double edged crack specimens. In another test, the crack ran straight between two symmetrically located twin cracks. Results of these five tests were used to verify the dynamic crack curving criterion by Ramulu, et al., in which a reference distance of ro=1/~~128/pi*[KI/sigmaox*V(c,ci,c2)]**2~~ from the crack tip

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is incorporated into the maximum circumferential stress of minimum strain energy density criteris. The critical material property for crack curving in this thin polycarbonate sheet was found to be about ro = 0.5 mm.