Pergamon

Mechanics Research Communications, Vol. 24, No. 1, pp. 57–64 1997

0093-6413/97 $17.00 + .00

PII S0093-6413(96)00078-X

ON DYNAMIC CRACK INITIATION IN POLYCARBONATE UNDER MIXED-MODE LOADING

D. Rittel, R. Levin and H. Maigre [1]
Faculty of Mechanical Engineering, Technion
32000, Haifa, Israel

(Received 8 July 1996; accepted for print 1 November 1996)

Introduction

The effect of mode-mix on crack initiation (toughness and trajectory) is well documented both theoretically and experimentally for quasi-static fracture [1]. Dynamic fracture (single or mixed-mode) analysis is generally more complicated since inertial effects cannot be neglected [2].

Recent (mode II) shear impact experiments in notched steel and polycarbonate specimens have shown the operation of fracture mode transitions (brittle to ductile, including shear band formation) as a function of the impact velocity [3-5]. In this work we assess the extent to which each failure mechanism (opening *vs.* shear banding) operates as a function of the mode-mix mode by using two distinct specimen geometries containing sharp fatigue cracks rather than notches. Accordingly, either of dominant mode I or dominant mode II is achieved for impact velocities ranging from 15 to 60 m/s. Preliminary results are presented and analyzed.

General framework

Dynamic fracture of ductile materials is of considerable interest since most engineering materials are ductile to some extent. Furthermore, many of these materials are known to exhibit transtitions in their failure mode (ductile to brittle) according to the rate of loading. Recent work on steel [3] and on polycarbonate [4] has shown a very interesting similitude in these materials' response to side impact on notched plates. Their results show (within the investigated range of impact velocities) that for both materials, there exist a velocity under which the failure mode is of the opening type (mode I) whereas beyond this velocity

---

[1] LMS Ecole Polytechnique, 91128 Palaiseau, Cédex France

adiabatic shear band forms at the tip of the notch and failure initiates by a shearing mechanism (e.g. mode II) without marked propagation of the flaw.

In these works the crack-tip fields were assessed qualitatively using shadow optical methods and the magnitude of each of the stress intensity factors (SIF) was not fully determined. In this paper, we present preliminary experimental results and address additional aspects of the failure mode transitions, namely:

1. Is the failure mode transition a result of the notch geometry which allows development of a negative mode I component [6]. In other words, does this transition occur also at the tip of sharp fatigue cracks?
2. Is the transition only observed for dominant mode II loading as investigated so far?

Experimental

We use an instrumented bar to apply and measure the transient forces and displacements applied to the specimens, as shown in Fig. 1. Dominant I is achieved through the use of CCS (Compact Compression Specimen) [7]. Dominant mode II experiments are carried out by applying side impact to fatigue precracked plates. A common point to all these experiments is that due to unsymmetrical loading, mode mixity develops. The investigated material was commercial polycarbonate supplied in the form of 12.7 mm thick plates.

Fatigue cracks were carefully grown in each specimen on a typical length of 2-3 mm. Such cracks induce two significant changes with respect to notches: the first is a condition of friction at the crack faces and the second is that negative mode I cannot develop as it would mean interpenetration of the crack flanks. To account for friction, we do not make use of the linear-elastic path independent H-integral [8-9] which was used in previous work. Rather, we adopted a hybrid numerical-experimental approach to assess the dynamic stress intensity factors by applying the experimentally recorded forces to a F.E. model into which contact and frictional conditions have been included while the coefficient of friction has been fixed to μ=0.4 [10]. The reason for choosing this value is purely arbitrary since the accurate value of μ cannot be simply assessed so that we use it for comparison purposes only.

Results & Discussion

A detailed description of the various experiments carried out will be given later. At this stage we will report characteristic results for lower and higher impact velocity experiments to illustrate specific points. The experimental results pertaining to dominant mode II and dominant mode I experiments are summarized in table I. For the dominant mode II experiments, we observed qualitatively the same material response than that reported by Ravi-Chandar for polycarbonate [3] and Kalthoff for steel [4]. At lower impact velocities (up to about 30 m/s), fracture proceeds at an initial kink angle of about 40° (rather than 70°) whereas at higher impact velocities, such as 60 m/s, damage becomes localized at the tip of the crack in the form of an adiabatic shear band which does not extend for more than 1-2 mm (Fig. 2). Consequently, it appears that the transition in failure modes is not the sole result of the crack-tip geometry which allows (for notches) negative mode I to develop but it is also observed to occur at the tip of sharp fatigue cracks. However the observed angles are smaller to 70° as would be the case for a brittle failure governed by a maximum normal stress criterion.

Typical results obtained for dominant mode I experiments show that fracture proceeds at an initial angle which does not exceed 40° regardless of the impact velocity. Yet, examination of the fracture surfaces and crack morphology in the immediate vicinity of the initiation area discloses the remains of an initial damage zone which is only fully discernable for higher impact velocity (Fig. 3). This damage zone reminds of the above mentioned adiabatic shear band. This is an important point which was not addressed so far as it suggests that the occurrence of adiabatic shear bands is not restricted to dominant mode II loading conditions. Rather, this failure mechanism is triggered as the result of the mode mixity which characterizes the reported experiments.

In Figs. 4 and 5 we have summarized results of the evolutions of the stress intensity factors which were calculated for the reported experiments. As expected, for each type of experiment either mode I or mode II stress intensity factor is dominant.

For the shear experiments, the mode I SIF is null for the most part of the duration analyzed. It is only at relatively long times (over 140 μs) that the mode I SIF becomes positive, which means tentative opening of the crack. The evolutions of the SIF's look generally similar regardless of the impact velocity. Specimen PC2 fractured at an angle of about 38° which can be explained using the maximum energy release rate for mixed mode [11]. However, specimen PC12 did not fracture in a similar way. Consequently, it is reasonable to assume that the observed crack-tip damage has nucleated and grown during the early (pure) mode II phase. This phase corresponds to maximal shear developing at zero angle with respect to the crack line.

Considering the higher *vs.* lower velocity mode I experimental results, it can be noted that they too look rather similar in their general appearance. However the similarity no longer holds when the actual values reached by each SIF are examined. Specifically, even if mode II is the minor mode here, increasing the impact velocity causes it to reach increasingly higher values at early times.

The two kinds of experiments can now be tentatively conciled by assuming the existence of a *threshold value for* K_{II} (at these high impact velocities) beyond which adiabatic shear band instability will be triggered. From our "mode II" results it seems that this value should be close to 4 MPa√m. The shear band will probably grow by consuming most of the impact energy so that it does not necessarily open as a result of the subsequent positive mode I values which develop later in the shear experiments. Back to the "mode I" experiments it can be noted that K_{II} reached 4 MPa√m for specimen CCS 15 (Fig. 4b) and fracture was detected at this instant whereas CCS 14 (Fig. 4a) did not cross this threshold and failure occurred later.

The proposed criterion relies on crack-tip parameters rather than on the impact velocity so that it may provide a basis for comparing various experiments. Further undertanding should be gained by considering that a new material surrounds the crack-tip as an adiabatic shear band forms.

Conclusions

Two types of dynamic crack initiation experiments (dominant mode II and dominant mode I) have been systematically conducted on fatigue precracked commercial polycarbonate specimens.

The experiments show that the reported transition in failure mechanisms occurs also at the tip of fatigue cracks.

Localized damage has also been observed for high impact velocity of dominant mode I specimens which fracture by subsequent opening.

Mode II and mode I observations of localized damage can be conciled by assuming the existence of a threshold value for the mode II stress intensity factor beyond which the instability is triggered in the form of a shear band. Failure may (or may not) follow by subsequent opening of a crack at angles of about 40° with respect to the crack line.

Acknowledgment

This research is supported by the Israel Science Foundation and the Technion VPR New York Metropolitan Research Fund. Support from the Arc en Ciel/Keshet cooperation program is also acknowledged by the authors.

References

1. Lawn, B. (1995), *Fracture of Brittle Solids* - Second Edition, Cambridge University Press, Cambridge.
2. L.B. Freund (1990), *Dynamic Fracture Mechanics,* Cambridge University Press, Cambridge .
3. Kalthoff, J.F. (1988), Shadow optical analysis of dynamic fracture, *Optical Engng*, **27**, 835-840.
4. K. Ravi Chandar, (1995), "On the failure mode transitions in polycarbonate under dynamic mixed mode loading", *International Journal of Solids and Structures*, Vol. **32** No. 6/7, 925-938.
5. Zhou, M., Rosakis, A.J. and Ravichandran, G., (1995), Dynamically propagating shear bands in impact-loaded prenotched plates, *SM Report 94-01*, California Institute of Technology, Pasadena CA.
6. Lee, Y.J. and Freund, L.B. (1990), Fracture initiation due to asymmetric impact loading of an edge cracked plate. *J. Appl. Mech.* **57**, 104-111.
7. Rittel, D., Maigre, H and Bui, H.D. (1992), A new method for dynamic fracture toughness testing, *Scripta Metallurgica et Materialia*, **26**, 1593-1598.
8. Bui, H.D and Maigre, H. (1988), "Facteur d'intensité des contraintes tiré des grandeurs mécaniques globales", *C.R. Acad. Sc. Paris*, **306** II, 1213-1216.
9. Bui, H.D., Maigre, H. and Rittel, D. (1992). "A new approach to the experimental determination of the dynamic stress intensity factor., *Int. J. Solids Structures*, **(29)** No. 23, 2881-2895.
10. ANSYS User's Manual, Swanson Analysis Systems Inc., 1994.
11. Rittel, D. and Maigre, H. (1996), A study of mixed-mode dynamic crack initiation in PMMA, submitted to *Mechanics Research Communications.*

spec.	V_imp	t_{gage}	angle	shear band
	[m/s]	[μs]	[°]	
CCS14	22	115	27-32	no
CCS15	45	79	34-38	yes
SHEAR2	25	–	≈38	no
SHEAR12	60	–	none	yes

Table 1: Experimental results. Fracture times (t_{gage}), when available, are measured using timing wires. The fracture angles do not exceed 40°. Note the observation of shear bands developing at the crak-tips when the impact velocity is increased.

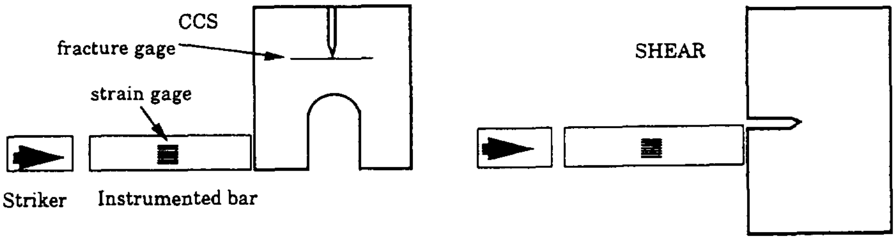

Figure1: Experimental setup. Dominant mode I is achieved using C(ompact) C(ompression) S(pecimens) and dominant mode II by side impact (shear) on notched plated. Fracture gages are sometimes used with CCS.

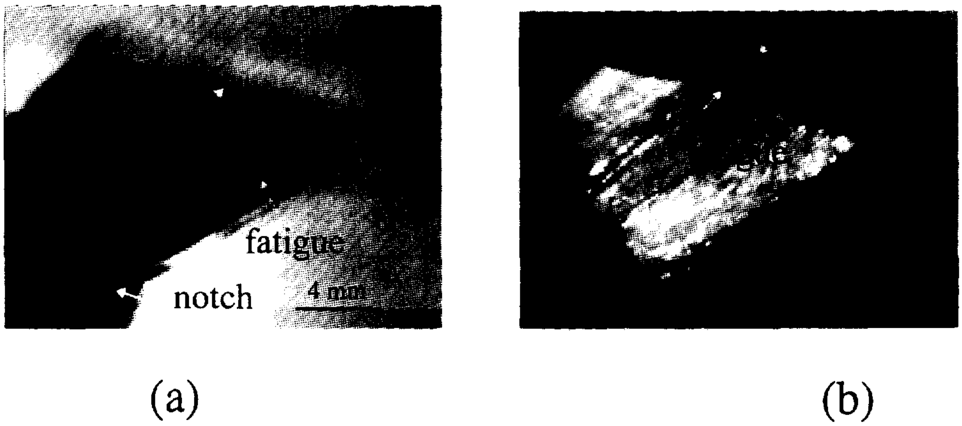

Figure2: (a) and (b). Adiabatic shear band observed at the tip of a fatigue crack. Shear specimen. The impact velocity was about 60 m/s. (a) transmitted and (b) reflected light. Note the planar shape of the band which extends across the thickness of the specimen.

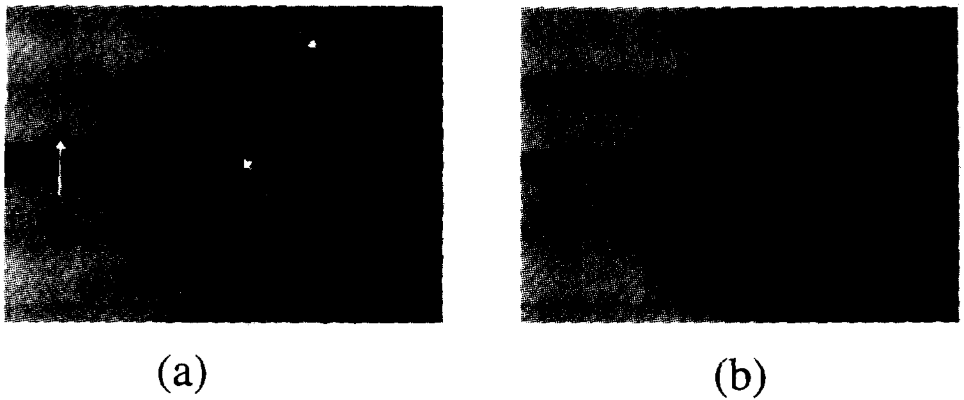
(a) (b)

Figure3: Side views of CCS. Reflected light. (a) impact velocity v =60 m/s. The crack proceeds at 35° w/r to the fatigue precrack. Note the damage zone at the beginning of the fast propagating crack. (b) impact velocity v =17.5 m/s. The angle is similar but no damage zone is discernable.

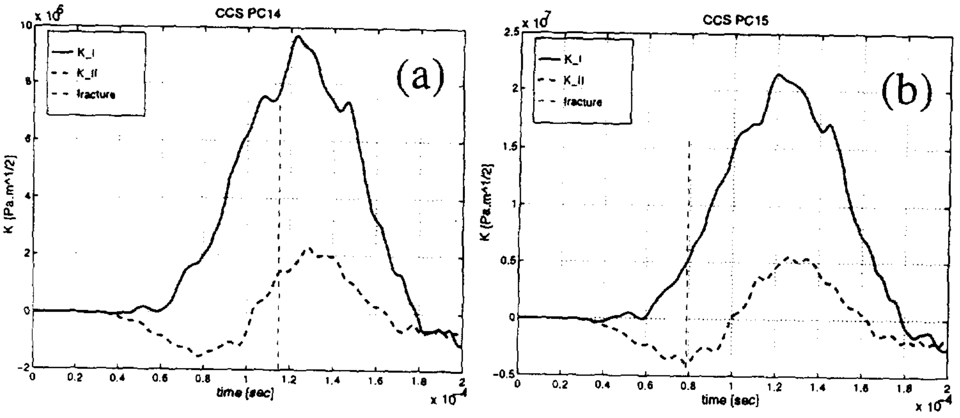

Figure4: Typical evolutions of dynamic K_I (solid) and K_{II} (dashed) for (a) CCS14 (v=22 m/s) and (b) CCS 15 (v=45 m/s) specimens. Note the higher K values in (b) due to increased impact velocity.

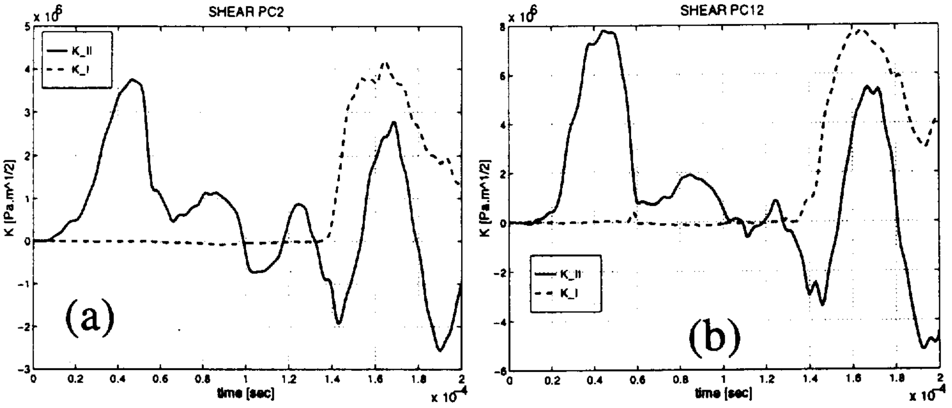

Figure5: Typical evolutions of dynamic K_{II} (solid) and K_I (dashed) for (a) shear 2 (v=25 m/s) and (b) shear 12 (v=60 m/s) specimens. Note the higher K values in (b) due to increased impact velocity.