Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 6 (2017) 83–89

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XXVII International Conference "Mathematical and Computer Simulations in Mechanics of Solids and Structures". Fundamentals of Static and Dynamic Fracture (MCM 2017)

Experimental investigation of dynamic crack propagation in PMMA plates

Nikita Kazarinov [a,*], Ivan Smirnov [a], Yuri Sudenkov [a], Yuri Petrov [a,b], Viacheslav Slesarenko[c]

[a]*Saint Petersburg State University, Saint Petersburg, 199034, Russia*
[b]*Institute of Problems of Mechanical Engineering (Russian Academy of Sciences), Saint Petersburg, 199178, Russia*
[c]*Lavrentiev Institute of Hydrodynamics (Russian Academy of Sciences, Siberian branch), Novosibirsk, 630090, Russia*

Abstract

In this paper we present experimental data on dynamic crack propagation in square PMMA plates of two types – 3.5 and 20 mm thick. Samples were loaded dynamically (mode I loading type) and crack tip position was registered using high speed camera. Explosion of a copper wire due to high electrical current was used to load faces of the initially prepared cracks. In order to investigate stress intensity factor (K_I) history, method of caustics was applied. Thick samples demonstrated considerably higher values of final crack travel distance and higher crack velocity values. Additionally, dependence of stress intensity factor on crack velocity was observed.

Peer-review under responsibility of the MCM 2017 organizers.

Keywords: crack propagation, dynamic fracture, stress intensity, caustic, PMMA

* Corresponding author. Tel.: +7 964 366 64 64.
E-mail address: n.kazarinov@spbu.ru

2452-3216
Peer-review under responsibility of the MCM 2017 organizers.
10.1016/j.prostr.2017.11.013

Nomenclature

V	crack velocity (m/s)
K_I	mode I stress intensity factor ($MPa\sqrt{m}$)
C	condenser capacity (μF)
U	condenser charge voltage (kV)
E	energy stored in condenser (J)
$D(t)$	caustic diameter (m)
z_0	distance from the sample to the shadow zone (m)
c	shadow optical constant
d	sample thickness (m)

1. Introduction

Dynamic crack propagation is one of the most studied areas of dynamic fracture mechanics. This phenomenon has been studied theoretically (Freund 1998, Broberg 1960), experimentally (Ravi-Chandar and Knauss 1984a,b,c, Dally 1979) and numerically (Xu and Needleman 1994, Kazarinov et al. 2014, Bratov and Petrov 2007), however there are still many unsolved problems in this area, such as problem of a limiting crack velocity (Livne 2008, Sharon and Fineberg 1999) and ambiguity in stress intensity factor – crack velocity dependence (Dally et al. 1985).

One should note here, that two main types of experiments on dynamic crack propagation are usually carried out – with dynamic (Ravi-Chandar and Knauss 1984, Kalthoff and Shockey 1977) and quasistatic (Fineberg et al. 1992, Kalthoff 1983) loading. In both cases transient effects should be taken into account, as propagating crack tip generates time-dependent stress-strain state in the sample with multiple travelling waves and corresponding effects (Kalthoff and Shockey 1977). Both experimental approaches are time-consuming, since specimens need to be very thoroughly prepared and registration of a moving crack tip position and stress field, surrounding it, requires special equipment and precise synchronization. Moreover, for the case of dynamic loading custom testing machines are usually designed in order to apply pressure pulses to the samples.

In this work we present experimental results on dynamic crack movement in PMMA square plates specimens of two thicknesses –3.5 and 20 mm. Samples were loaded dynamically with pressure being normally applied to the crack faces and crack tip position was registered throughout the experiment. In addition to this data, dependence of stress intensity factor (K) on time was investigated.

2. Specimens and experimental techniques

Square PMMA plates of 200 mm side and 3.5 and 20 mm thickness were tested. Initial crack was 50 mm long. Tip of the initial crack was sharpened using a razor blade. Mechanical properties of the tested PMMA are listed in table 1.

Table 1. Material properties of the tested PMMA

Young's modulus (GPa)	5.9
Poisson's ratio	0.33
Density (kg/m^3)	1180
Ultimate stress (MPa)	75
Ultimate stress intensity factor (MPa$\sqrt{\text{m}}$)	1.1
Longitudinal wave velocity (m/s)	2720
Transversal wave velocity (m/s)	1370
Rayleigh wave velocity (m/s)	1277

The samples were loaded using conductor explosion technique. The exploding copper wire (0.2 mm in diameter) was placed between the crack faces perpendicular to the plane of the plate. The wire was linked to the condenser with the following parameters: capacity C = 1.0 μF; the charge voltage, $U \leq 25$ kV; the stored energy, $E \leq 312$ J. The setup was equipped with a special trigger device and electric current sensor, which provided possibility to synchronize discharge of the condenser leading to the wire explosion and activation of a high-speed camera used for the registration of the crack propagation. In order to create the acoustic contact between the wire and the crack faces a PET film was used. One sample was used several times.

The crack front movement was registered using streak camera (BIFO K008) and slit-type scanning of an image. A laser generated light beam firstly passed through the sample in the region of interest and then through a special frame with a slit aligned with the crack trajectory. Afterwards, the beam passed through a special lens and finally was registered by the streak camera (see fig. 2 for details). Thus, diameter and location of a caustic was registered during the test. The detailed schemes and descriptions of this type of experiments are presented in (Smirnov and Sudenkov 2013).

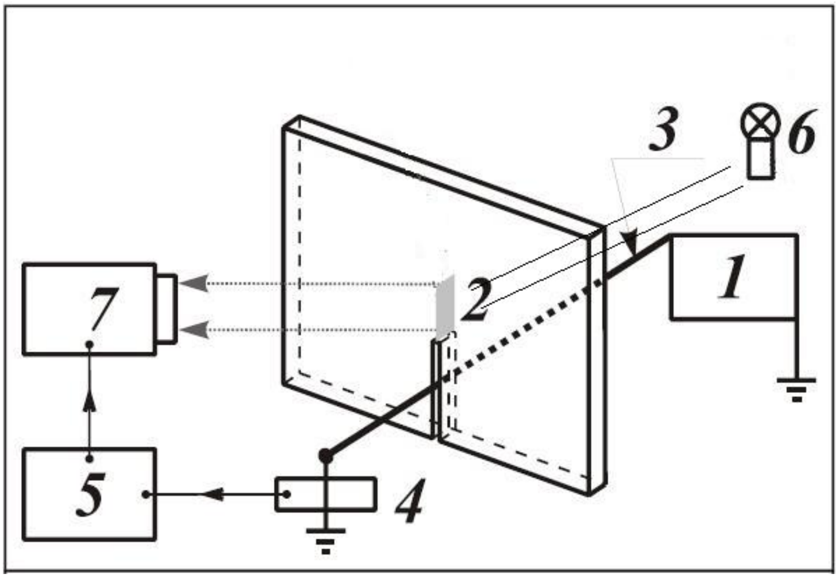


Fig. 1. Scheme of the experimental setup: 1 – condenser, 2 – crack, 3 – exploding copper wire, 4 – electric current sensor, 5 – electric pulse generator, 6 – light source, 7 – streak camera

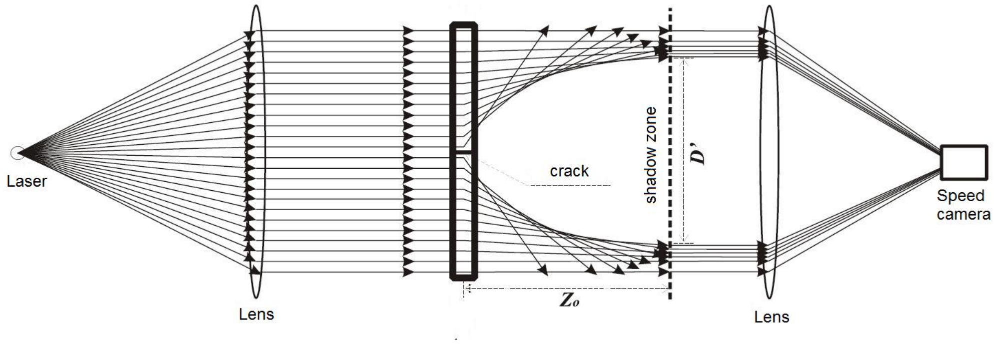


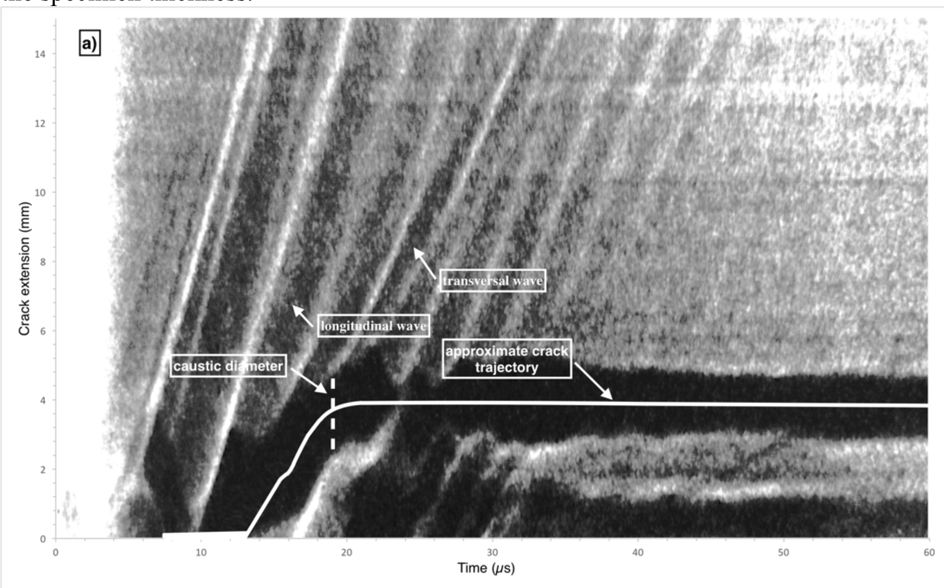
Fig. 2. Scheme of the applied shadow optical method.

The caustic near the crack tip was registered using shadow optical method (see Kalthoff 1986 for details). Since the light beam that passed through the sample was cut by the slit frame, the camera registered front and back ends of the caustic during the test. Thus, caustic diameter was registered along crack trajectory rather than across, which is a common practice.

Mode I stress intensity factor values (K_I) were calculated according to formula (1)], which reads as (Kalthoff 1986):

$$K_I = \frac{2\sqrt{2\pi}}{3(2.5)^{5/2} z_0 c d} D(t)^{5/2} \quad (1).$$

In (1) $D(t)$ is time-dependent caustic diameter, z_0 is distance from the sample to the shadow zone, c is shadow optical constant, d is the specimen thickness.



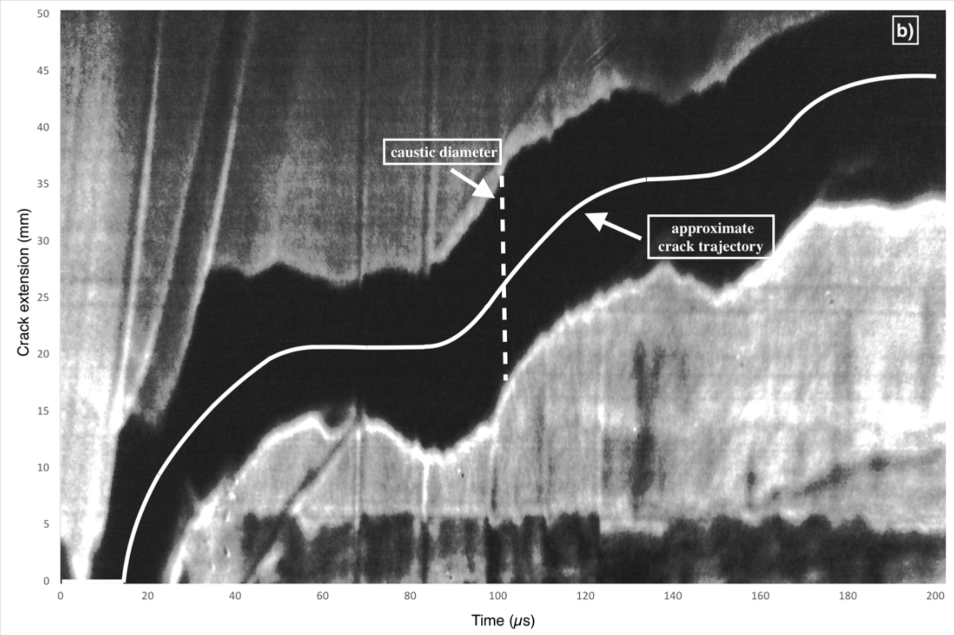


Fig. 3. Caustic history with marked elastic waves and approximate crack tip path (a – 3.5 mm plate, b – 20 mm plate)

3. Results

Typical caustic history, obtained from the streak camera is shown in figure 3. The figure 3 depicts approximate dependence of the crack tip position on time, which roughly coincides with the caustic center. It is possible to compare velocity of the crack tip with velocities of longitudinal and transverse waves, measuring the inclines of the corresponding patterns.

Dynamic loading resulted in almost monotonous growth of the crack for the 3.5 mm samples, while in case of thick 20 mm plates stepwise crack propagation was observed. The stepped trajectory shape was due to reflected waves, arriving from the sample edges. In general, crack tip covered much longer distance for the case of 20 mm plates. While for 3.5 mm samples crack extension ranged from 3.5 to 5 mm, the crack tip travelled up to 47 mm distance for the 20 mm samples.

Differentiation of crack position by time provided crack tip velocity results. The corresponding dependencies are shown in figure 4. The observed oscillations should be treated as instantaneous crack velocities and averaged values should be assessed. Crack velocity values do not exceed the theoretical limit $-\ C_r\ -$ Rayleigh wave velocity (Freund 1998). As seen from the figure 4, the crack velocity reaches its maximum, when crack starts to propagate, decreasing to zero. However, crack acceleration is observed for the case of the thick samples. Fluctuations of the crack velocity correspond to well-known patterns of the ruptured areas (Ravi-Chandar and Knauss 1984b) - fragmentary (large pieces), scaly, parabolic and mirror, which were found due to post-mortem investigation of the samples.

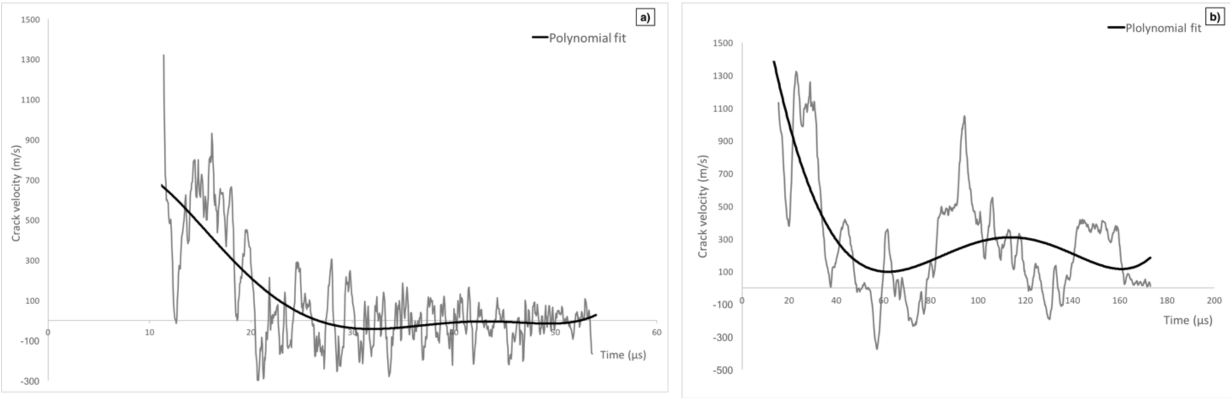


Fig. 4. Crack velocity – time dependence (a – 3.5 mm, b – 20 mm)

Figure 5 depicts dependence of the stress intensity factor $K_I(t)$ on time. For both 3.5 mm and 20 mm samples $K(t)$ reaches its maximum when the crack starts to propagate. The maximum value for the both cases exceeds static value of critical stress intensity factor (K_{Ic}). Considering $K - V$ dependence issue ($V -$ crack velocity) (Dally et al. 1985), one can note, that initial high values of K correspond to high initial crack velocity with subsequent drop in both crack velocity and K values. 20 mm samples reveal significantly higher K_I values. Despite the fact that dynamic loading was applied, the results differ from those obtained in (Ravi-Chandar and Knauss 1984c), where constant crack velocity could correspond to considerable K variation. This effect might be due to the fact, that relatively long loading pulse was applied in the work by Ravi-Chandar and Knauss, while short pulse was applied in the studied case.

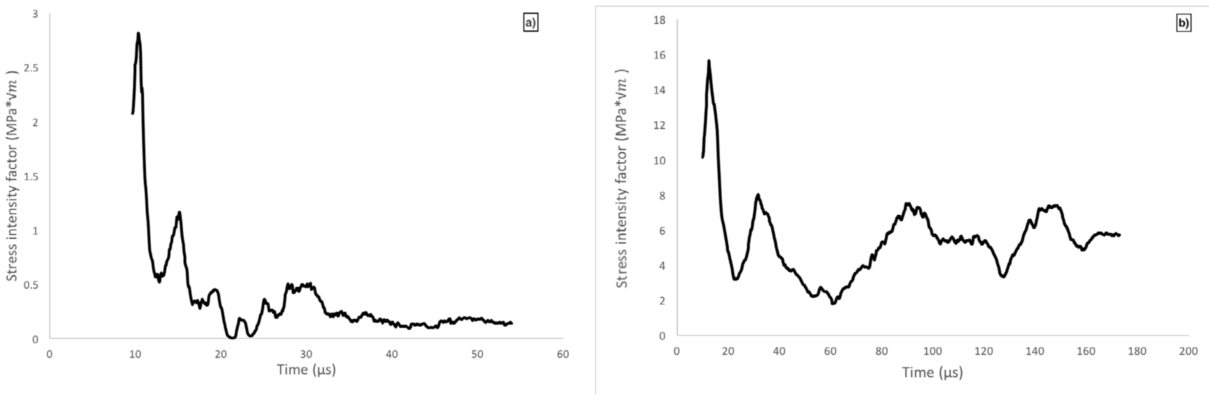


Fig. 5. Dependence of stress intensity factor on time (a – 3.5 mm, b – 20 mm).

4. Conclusion

Dynamic crack propagation was studied in PMMA plates of two thicknesses – 3.5 mm and 20 mm. Specimens with initial cracks were loaded dynamically using explosion of the copper wire, placed between the crack faces. Crack tip position was registered using high speed streak camera, which also provided possibility to assess caustic diameter and therefore to measure current stress intensity factor. Experiments revealed, that crack propagates to significantly higher distance in case of the thick samples. In addition to this, crack velocity appeared to be higher for the 20 mm plates, however average crack velocity did not exceed the theoretical limit – velocity of the Rayleigh waves. Crack movement initiation corresponds to both maximal crack velocity and maximal stress intensity factor values, which both decrease subsequently. Thus, dependence of the stress intensity factor on crack velocity was observed, which contradicts well-known classic experiments on dynamic loading of plates (Ravi-Chandar and Knauss 1984a,b,c), where no dependence was observed. Such a discrepancy might be attributed to different loading pulses – in work by Ravi-Chandar and Knauss relatively long pressure pulses were applied, while wire explosion resulted in spatially localized short pressure pulses.

Acknowledgements

The work was supported by RFBR (16-31-60047 mol_a_dk) and grant of the President of Russian Federation (MK-2587.2017.1)

References

Freund L.B., 1998. Dynamic Fracture Mechanics. Cambridge University Press, Cambridge, pp. 563.

Broberg K.B., 1960. The propagation of a brittle crack. Archiv fur Fysik 18, 159–192.

Ravi-Chandar K., Knauss W., 1984a. An experimental investigation into dynamic fracture-I. Crack initiation and arrest. International Journal of Fracture 25, 247-262.

Ravi-Chandar K., Knauss W., 1984b. An experimental investigation into dynamic fracture-II. Microstructural aspects. International Journal of Fracture 26, 65-80.

Ravi-Chandar K., Knauss W., 1984c. An experimental investigation into dynamic fracture-III. On steady-state crack propagation and crack branching. International Journal of Fracture 26, 141-154.

Xu X.-P., Needleman A., 1994. Numerical simulations of fast crack growth in brittle solids. J. Mech. Phys. Solids 42(9), 1397-1434.

Kazarinov N.A., Bratov V.A., Petrov Yu.V., 2014. Simulation of Dynamic Crack Propagation under Quasi-Static Loading. Doklady Physics, 454(6), 557-560.

Bratov V., Petrov Y., 2007. Application of Incubation Time Approach to Simulate Dynamic Crack Propagation. International Journal of Fracture 146, 53-60.

Dally J.W., 1979. Dynamic photoelastic studies of fracture, Experimental Mechanics, 19, 349-36.

Dally J.W., Fourney W.L., Irwin G.R., 1985. On the uniqueness of the stress intensity factor – crack velocity relationship. International Journal of Fracture 27, 159-168.

Kalthoff J.F., Shockey D.A., 1977. Instability of cracks under impulse loads. J. Appl. Phys. 48(3), 984-993

Fineberg J., Gross S.P., Marder M., Swinney H.L., 1992. Instability in Crack Propagation. Physical Review, 45(10), 5146-5154.

Sharon E., Fineberg J., 1999. Confirming the continuum theory of dynamic brittle fracture for fast cracks. Nature 397, 333-335

Livne A., Cohen G., and Fineberg J., 2008. Fast fracture in slow motion. Proceedings of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis ESDA08 July 7-9, 2008, Haifa, Israel.

Kalthoff J.F., 1983. Workshop on Dynamic Fracture, California Institute of Technology, 11-25

Smirnov I., Sudenkov Y., 2013. Crack Propagation in PMMA Plates under Various Loading Conditions. Proceedings of the 13th International Conference on Fracture June 16–21, 2013, Beijing, China

Kalthoff J.F., 1986. The shadow optical method of caustics, in: A.S. Kobayashi (Ed), Handbook on Experimental Mechanics, Prentice Hall, Englewood Cliffs, New Jersey.