Advanced Materials Research Vols. 41-42 (2008) pp 169-173
Online available since 2008/Apr/08 at www.scientific.net

doi:10.4028/www.scientific.net/AMR.41-42.169

Discontinuous Growth Mechanisms of Mode II Crack under High-speed Impact Conditions

Wei Ma

Institute of Mechanics, Chinese Academy of Sciences,
15 Beisihuanxi Road, Beijing, 100080
email: watwm@imech.ac.cn

Keywords: plate impact tests; dynamic fracture; failure mode transition; intersonic crack extension; discontinuous crack growth model

Abstract. A recoverable plate impact testing technology has been used for studying the growth mechanisms of mode II crack. The results show that interactions of microcracks ahead of a crack tip cause the crack growth unsteadily. Failure mode transitions of materials were observed. Based on the observations, a discontinuous crack growth model was established. Analysis shows that the shear crack grows unsteady as the growth speed is between the Rayleigh wave speed c_R and the shear wave speed c_s; however, when the growth speed approaches $\sqrt{2}c_s$, the crack grows steadily. The transient microcrack growth makes the main crack speed to jump from subsonic to intersonic and the steady growth of all the sub-cracks leads the main crack to grow stably at an intersonic speed.

Introduction

So far, the fracture mechanisms in mode II crack have not been completely understood due to the technical restrictions of the current testing means, even though a great number of investigations have been conducted and many interesting phenomena have been observed [1-5]. For further investigation of fracture mechanisms of mode II crack, it is needed to improve current experimental technology and develop innovative analytical method. This paper addresses some aspects of the problem.

The studies [2, 3] on the failure behavior of high strength steel under the dynamic loading conditions of mode II crack show that low speed impact induces cleavage fracture and the maximum hoop stress criterion [8] governs the behaviors of crack initiation and growth. When the impact speed was above a critical value, a failure mode transition from crack fracture to shear band failure was observed, and a failure mechanism transition from cleavage fracture to ductile shear failure was also observed. In similar investigations [4, 5], the relevancy of loading rate to crack growth mechanisms and failure mode of materials is studied. The results demonstrated that at low loading rates, only a plastic zone was formed at crack tip, but no crack started; at moderate loading rates, a brittle crack began and the failure mode changed from ductile to brittle; and at high loading rates, the crack formed and advanced along the original crack line but was arrested in the specimen. Postmortem microstructural examination of the failure surface indicated that the maximum shear stress criterion governed the fracture process.

Recently, much attention focuses on shear-dominated intersonic crack extension mechanisms. Intersonic cracking has been directly observed in asymmetrical impact tests on a specimen consisting of a homogeneous and isotropic solid with an artificial weak band plane by Rosakis et al. [6, 7]. In the study, the shear cracks propagated the shear cracks propagated initially with a speed just above the shear wave speed c_s, then accelerated sharply to the longitudinal wave speed c_l, and finally approached a steady intersonic speed $\sqrt{2}c_s$. Motivated by the experimental observations, many researchers have paid great attention to intersonic cracking [8-10]. The study [8] shows that, when a shear crack propagates along a weak plane, a daughter crack first initiates in front of the crack tip, and then joins with the mother crack, which may cause the crack to propagate with intersonic speeds. The interaction of the "mother-daughter" crack is responsible for a subsonic shear crack to jump over the forbidden velocity zone between the Rayleigh wave speed c_R and the shear wave speed c_s. The numerical simulations [9, 10] also demonstrate that a finite peak stress ahead of mother crack is the only possible mechanism of daughter crack nucleation.

In the study, in order to understand the mechanisms of mode II crack growth under high-speed impact conditions, an improved plate impact testing technique was developed and the dynamic failure tests of Hard-C $60^{\#}$ steel was conducted. In addition, based on the experimental observations, a discontinuous transient crack growth model is proposed and the relevant dynamic mechanisms of mode II crack initiation and growth are discussed following the energy principle of dynamic fracture mechanics.

Experimental procedure and results

Hard-C $60^{\#}$ steel is chosen as the testing material. Before testing, the material was normalized by heat treatment to become brittle enough. Thus, we assume that the size of plastic process region at the dynamic crack tip, if it exists, is negligibly small and that the results of impacting experiments can be interpreted by using elastodynamic fracture theory. The impacting test was carried out on a pressure-shear gun. The configurations of impact tests and the geometrical dimensions of collision components are shown in Fig. 1. The experimental details can be found in [11].

Fig. 2 shows the micrographs of crack growth paths taking from the samples produced at the impact speed 151 m/s and 173 m/s respectively. As we see from the figure that, at low loading rate, the crack initiates and only one subcrack develops ahead of the crack tip (Fig. 2 *a*); but at high loading rate, six microcavities form and induce five subcracks growth (Fig. 2 *b*). It is noticeable that some interesting phenomena in this figure can be interpreted according to the classical fracture theory.

No surface tractions presenting at the notch tip means that the maximum hoop stress criterion [12] governs the initiation of a mode I crack. The facts that the intensity of compressive stress pulse is much larger than the yield limit of material and the residual opening displacement of crack face at the location of crack initiation as indicated by the labels (1) in this figure indicate that the mode I cracks have started with ductile initial mechanism. But the SEM image of the crack growth face with typical cleavage characteristic (Fig. 3) clearly demonstrates a brittle growth mechanism of the mode I crack (Fig. 2 *b*). These observations convincingly point out that, during the stage of crack initiation, the intensive compressive stress pulse has induced the plastic deformation and heating softening of material at crack tip; and the mode I crack fracture exhibits the mechanisms of ductile initiation and brittle growth.

As showing in Fig. 2 *b*, the subsequent growth of the crack is in the direction of compressive stress pulse propagation on which shear stress is maximal. Hence, the maximum shear stress criterion governs a mode II crack growth. Extensive dimpling and drawing on the dynamic fracture surface (Fig. 4) demonstrate that the ductile fracture has become the dominant failure mechanism of material. Actually, it is the large shear stress on the crack line that induces the heat production and plastic softening of material. From the statement above, we conclude that the crack fracture growth mode has undergone a transition from mode I to mode II, and the failure mode has also experienced a complex change from ductile initiation to brittle growth, and back again to ductile growth, after the dominant stress driving crack growth changes from the maximum hoop tensile stress at the crack tip to the maximum shear stress along the crack line.

Moreover, from the experimental result as showing in Fig. 2 *b*, we have seen that there is a need for further investigation on the discontinuous growth mechanism of crack.

Discontinuous crack growth model

Following the compressive stress-time profiles obtained in the shot at the impact velocities of 173 m/s [11], the energy dissipation rate can be determined as shown in Fig 5. The figure shows that the energy dissipates in four stages. The rapidly increasing stage of energy dissipation (OA in Fig.5) suggests several subcracks to initiate and grow ahead the crack tip simultaneously. The rapid and stable stage of energy dissipation (AB in Fig.5) implies either that no new subcracks form or that some subcracks do but arrest simultaneously. The abruptly decreasing stage of energy dissipation (BC in Fig.5) means some subcracks have joined each other and arrested. The low and slow stage of energy dissipation

(CD in Fig.5) suggests that the process of crack growth has stopped. Therefore, the fracture energy for the crack initiation and growth is only related to the first three stages of the energy dissipation process.

The main crack consists of five subcracks with length, l_k (k =1, 2, …5) (Fig. 2 *b*). In the model, the subcracks are assumed to grow steadily at uniform velocities and the special energy dissipated by each subcrack is proportional to its length, but the main crack advances unsteadily with a nonuniform velocity. The critical energy release rates for crack initiation are assumed to equal to the crack arrest fracture energy. Thus, the initiation times, t_{ik} (k =1, 2, …4) of the first four sub-cracks are determined from the energy dissipation-time curves (Fig. 5), and the ending times of sub-crack growth t_{ak} are determined by [13]

$$\frac{1-\mu^2}{E}\int_{t_{ik}}^{t_{ak}}\left[A_I(v)K_I^2 + A_{II}(v)K_{II}^2\right]dt = \Gamma_k, \quad \left(k = 1,\ 2,\ \cdots 5\right) \tag{1}$$

where $\Gamma_k = G_k/(l_k \times w)$is the rate of mechanical energy flow into the sub-crack tip per unit crack advance. G_k and w are respectively the energy dissipation of each subcrack and the width of the sample. The dimensionless functions $A_I(v)$ and $A_{II}(v)$ are universal functions of the crack speed v and the properties of materials [13, 14]. For the last sub-crack, the arrest time t_{a5} is determined from Fig.5, and the initiation time t_{i5} is obtained from the relationship (1).

Fig. 6 gives schematically the lengths of each subcrack and the positions of the main crack tip at different characteristic time t_{ik} and t_{ak}, (k = 1, 2, … 5) respectively. When the first subcrack advances with average velocity V_{a1}, the compressive stress pulses propagating with the longitudinal wave speed has reached the location where the second subcrack nucleates, and made it initiate at time t_{i2}. This implies that, on the macroscopic scale, the main crack grows suddenly longer and the growth velocities jump discontinuously from slow to fast. Note that, at this time, the second subcrack tip replaces the first subcrack tip to become the main crack tip. In the same way, subsequent initiation and growth of other subcracks induce the velocity jumps of crack growth. Presently, if assuming that the behavior of subcrack growth complies with the elastodynamic theory, the unsteady growth mechanism of the main crack can be explained by some interesting features of growth velocities.

The functional relationship of the crack tip varying with time can be established from the results shown in Fig. 6. By using the discontinuous transient crack growth model, the typical speed-time curves of crack growth at nonuniform speeds are obtained (Fig.7). At time t_{i1}, only the first subcrack initiates. Its nonuniform growth speed V_{a1} determines completely the growth mechanisms of the main crack at a subsonic speed. Then, the immediate initiation and growth of other subcracks make the growth speeds of the main crack increase sharply from the subsonic speeds lower than Rayleigh wave speed c_R to the intersonic speeds higher than shear wave speed c_s. That is, a transition of the main crack growth mechanisms from subsonic to intersonic has taken place. Subsequently, some of the subcracks stop growing, but others form and grow continuously. This leads the main crack to steadily grow about 100 ns at an intersonic speed of about $\sqrt{2}c_s$. Finally, when the first several subcracks stop advancing or joining each other, the mechanisms of main crack growth are completely dependent on the behaviors of the last unsteady growth subcrack. At the moment, the growth speed quickly decelerates to the subsonic levels and finally arrests in the specimen.

The previous studies [6-10] have revealed two interesting phenomena on intersonic crack growth: i) if crack growth speed is in the region of Rayleigh wave speed c_R and shear wave speed c_s, the energy release rate is negative so that dynamic fracture theory can not be used to describe the unsteady intersonic growth mechanisms; ii) the steady growth speed of a mode II crack should be either subsonic or intersonic, but the stable intersonic growth speed will constantly come close to $\sqrt{2}c_s$. Based on the discontinuous crack growth model, we can figure out that the precursive compressive stress pulses control the subcrack initiation mechanisms. Actually, whether the subcrack can initiate under the conditions of the asymmetrical impact loading is completely dependent on the instantaneous rate of energy flow toward crack tip or the intensity of stress pulse. The initial time is related to the propagation speed of stress pulse. Presently, the compressive stress pulse propagates at the longitudinal wave speed, which in all probability makes the subcracks initiate continuously in such shot time interval competing with the interval of longitudinal wave propagation. Hence, the continuous initiation and growth mechanisms of several subcracks ahead of crack tip cause a rapid increase of the main crack growth speed, which is responsible for the transition of the unsteady crack growth speeds from subsonic to intersonic. Generally, the continuous growth mechanisms of a single crack can be described by the elastodynamic theory of continuum mechanics. However, in the case of simultaneous initiation and growth of several cracks, the discontinuous growth mechanisms cannot be satisfactorily described in the theoretical framework. This may be probably the cause that induces the nonsensical conclusion of negative energy release rate. Nevertheless, according to the discontinuous crack growth model, the reasonable interpretation on the nonsensical concept is straightforward as doing above. Moreover, we have seen that the successive growth and connection among subcracks make the main crack grow steadily at a uniform intersonic speed of about $\sqrt{2}c_S$; whereas, the remnant question why the steady intersonic crack speeds approach the $\sqrt{2}c_S$ has yet not be understood clearly just through the qualitative analysis based on the model. Hence, it is needed more delicate and profound studies on the issue to quantitatively reveal the essence of the intersonic crack growth. In conclusion, by using the discontinuous transient crack growth model we can perceptually explain why the crack growth speed increases rapidly from subsonic to intersonic and can qualitatively describe the important traits of the intersonic crack growth speeds.

Summary

The asymmetrical compressive stress pulse can induce several microcracks ahead of the crack tip to nucleate and grow simultaneously. The interaction and coalescence among the subcracks are responsible for unsteady growth mechanisms of cracks. Failure mode transitions, both from a mode I to mode II crack and from cleavage to ductile fracture, were observed. Two main characteristics of intersonic crack growth, the forbidden speed regime between c_R and c_s and the steady limit speed $\sqrt{2}c_S$, are interpreted qualitatively according to the discontinuous crack growth model. The transient mechanisms like the nucleation, interaction and coalescence among the subcracks make the main crack growth speed surpass rapidly the forbidden speed regime, and stable growth of subcracks result in the steady intersonic growth of main crack.

References

[1] B.N. Cox, H, Gao, D. Gross and D. Ritted: Journal of the Mechanics and Physics of Solids. 53(3), (2005), p. 565

[2] J. F. Kalthoff: Proc. Int. Conf. on Photo-mechanics and Speckle Metrology. San Diego, Calif. Aug. 16-21 (1987), and Optical Engineering, Vol. 27, (1988), p. 835

[3] J. F. Kalthoff: Appl. Mech. Rev. Vol. 43, No. 5. Part. 2, (1990), p. S247

[4] K. Ravi-Chandar: International Journal of Solids and Structures. Vol. 32, No.6/7, (1995), p. 925

[5] K. Ravi-Chandar, J. Lu, B. Yang, and Z. Zhu: International Journal of Fracture. Vol. 101, (2000), p. 33

[6] A. J. Rosakis, O. Samudrala, and D. Coker: Science. Vol.284, No. 21, (1999), p.1337

[7] A. J. Rosakis, O. Samudrala, and D. Coker: Mat. Res. Innovat. 3, (2000), p. 236

[8] F. F. Abraham,and H. Gao: Physical Review Letters. Vol. 84, No. 14, (2000), p. 3113

[9] A. Needleman: J. Appl. Mech. Vol. 66, No. 4. (1999), p. 847

[10] P. H. Geubelle and D. V. Kubair: Journal of the Mechanics and Physics of Solids. Vol. 49, (2001), p. 571

[11] W. Ma and Z. Duan: ACTA Mechanica Sinica. Vol. 16, No.4, (2000), p. 335

[12] F. Erdogan and G. C. Sih: Journal of Basic Engineering. 85 D, 1963, p. 519

[13] W. Ma: Journal of Mechanics of Materials and Structures. To be published. (2007)

[14] Freund L.B., 1990. Dynamic Fracture Mechanics, Cambridge University Press, NY.

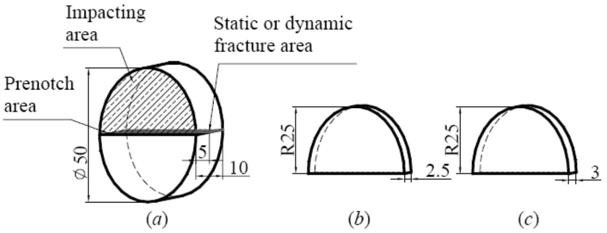

Fig. 1. The configurations and geometries of the crashing components used in this study including the specimen (*a*), transmission plate and flyer (*b*), and momentum plate (*c*).

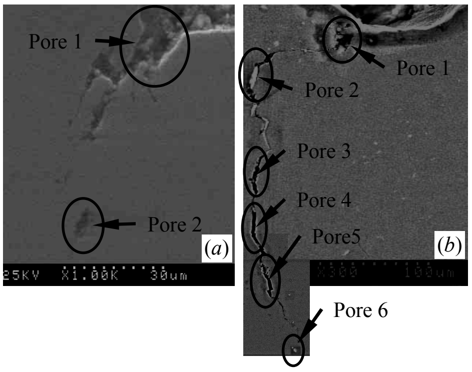

Fig. 2. The general microscopic view of the crack traces shows the main crack interaction with the micro-cracks. (*a*) the impacting speed is equal to 151 m/s, (*b*) the impacting speed is 173 m/s,

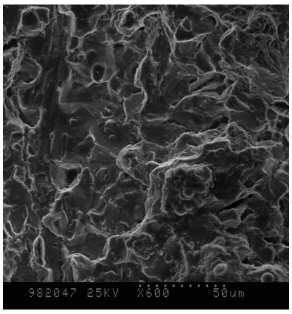

Fig. 3. The SEM image of the cleavage fracture features on the mode I crack surface.

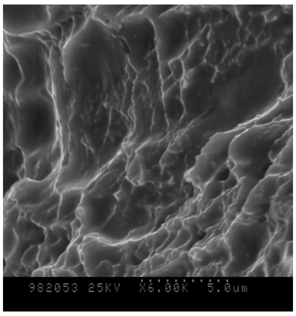

Fig. 4. The SEM image of the ductile fracture features on the mode II crack surface.

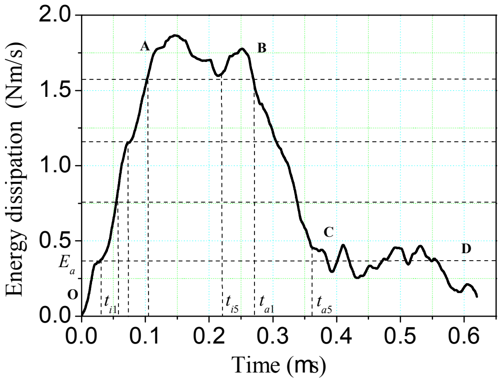

Fig. 5. The profile of energy dissipation rates *vs* time is obtained from the curves of the compressive stress pulse.

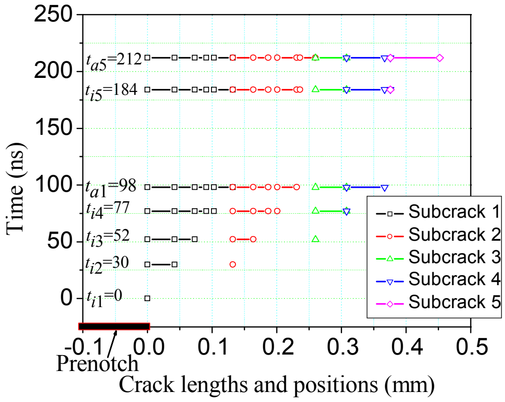

Fig. 6. The lengths of the subcracks and the positions of the main crack tip at different characteristic times.

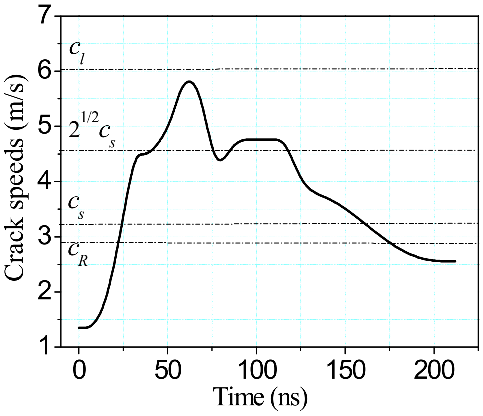

Fig. 7. The speed-time profiles of the main crack growth obtained by using the discontinuous growth crack model.

Structural Integrity and Failure, 2008
10.4028/www.scientific.net/AMR.41-42

Discontinuous Growth Mechanisms of Mode II Crack under High-Speed Impact Conditions

10.4028/www.scientific.net/AMR.41-42.169

DOI References

[1] B.N. Cox, H, Gao, D. Gross and D. Ritted: Journal of the Mechanics and Physics of Solids. 3(3), (2005), p. 565
doi:10.1016/j.jmps.2004.09.002
[3] J. F. Kalthoff: Appl. Mech. Rev. Vol. 43, No. 5. Part. 2, (1990), p. S247
doi:10.1115/1.3120818
[4] K. Ravi-Chandar: International Journal of Solids and Structures. Vol. 32, No.6/7, (1995), p. 925
doi:10.1016/0020-7683(95)90028-4
[5] K. Ravi-Chandar, J. Lu, B. Yang, and Z. Zhu: International Journal of Fracture. Vol. 101, 2000), p. 33
doi:10.1023/A:1007639126484
[6] A. J. Rosakis, O. Samudrala, and D. Coker: Science. Vol.284, No. 21, (1999), p.1337
doi:10.3171/foc.1999.7.6.12
[7] A. J. Rosakis, O. Samudrala, and D. Coker: Mat. Res. Innovat. 3, (2000), p. 236
doi:10.1515/JMBM.2000.11.1-3.191
[8] F. F. Abraham,and H. Gao: Physical Review Letters. Vol. 84, No. 14, (2000), p. 3113
doi:10.1103/PhysRevLett.85.622
[10] P. H. Geubelle and D. V. Kubair: Journal of the Mechanics and Physics of Solids. Vol. 49, 2001), p. 571
doi:10.1016/S0022-5096(00)00041-7
[12] F. Erdogan and G. C. Sih: Journal of Basic Engineering. 85 D, 1963, p. 519
doi:10.1021/jo01038a506
[10] P. H. Geubelle and D. V. Kubair: Journal of the Mechanics and Physics of Solids. Vol. 49, (2001), p. 571
doi:10.1016/S0022-5096(00)00041-7