FUNDAMENTAL PROBLEMS IN DYNAMIC FRACTURE

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ABSTRACT

Following a brief general review of developments in dynamic fracture, four problem areas in this discipline are examined: Crack initiation under stress wave loading, crack propagation, branching, and arrest. These topics are discussed from the viewpoint of understanding the physical fracture process at the tip of dynamically loaded cracks. Time scales, other than those governed by the elastic wave speeds, are important in connection with dynamic fracture. These time scale differences are connected with the establishing of the process zone which consists of an ensemble of micro cracks. Direct evidence of these micro cracks is reviewed as well as the importance of strain rate history effects in dynamic fracture.

KEYWORDS

Dynamic fracture; stress waves; dynamic crack initiation; fast running cracks; crack branching; crack arrest; dynamic crack tip autonomy.

INTRODUCTION

Following the development of the wave character of light, wave motion in solids has been studied as early as 160 years ago by Navier and Poisson. However, it was not until the early 1870's that John Hopkinson (1872) investigated the strength behavior of iron in wire form under high rates of loading through drop weight experiments. Taking into account the generation and reflections of stress waves, he found that the wire could withstand stress pulses without yielding, that were substantially greater than the static yield stress. In a somewhat more detailed analysis, based on tests by Bertram Hopkinson, John Hopkinson's son, G.I. Taylor (1946) calculated (much later) this stress to be on the order of 1.5 to 1.7 times the yield stress for a duration of about 100 μsec. Today, we accept almost routinely the fact that under high rates of loading materials respond with stress levels significantly above those encountered in static loading situations.

A BRIEF REVIEW OF THE "STATE OF THE ART"

Since John Hopkinson's work and his son's Bertram Hopkinson there seems to have been little work done on the effect of wave action on fracture - other than the pursuit of understanding dynamically induced stress states as a precursor to failure. The end of the last century and roughly the first half of the present one saw a firming-up of the formulation of problems in dynamic elasticity and solution for certain classical initial boundary value problems that laid the groundwork for our understanding of wave motion in solids and along their boundaries. Impact tests for engineering purposes, such as the Izod and Charpy tests, were then developed with a minimum of dynamic stress analysis. In the second half of this century the mechanics of quasistatic fracture via crack instability in engineering materials took hold. However, because of a larger degree of analytical and experimental complexity involved in problems of dynamic as opposed to quasistatic fracture the investigations of the former have lagged consistently behind the static counterparts. No doubt this lag was also due to the preponderance of pressing engineering problems of non-dynamic character.

In order to appreciate where we are today in understanding dynamic crack propagation problems, we need to recognize that for experimental work one needed to develop the relatively elaborate machinery for recording high-speed events (photography). Here Schardin's laboratory, now the Institut fur Festkörpermechanik of the Fraunhofer Gesellschaft in Freiburg, West Germany, has contributed extensively and consistently to the experimental methods employed today in dynamic fracture. We need only remind ourselves of the multiple spark (Cranz-Schardin) camera, Kerkhof's dynamic wave modulation of fracture surfaces, Manogg's shadowspot method (caustics) promulgated vigorously by P. Theocaris, to recognize the basic contributions made by that laboratory. Later developments elsewhere of high-speed photography in the form of turbine driven and image converter cameras have aided those developments. If one adds to these accomplishments the demonstration of dynamic photoelasticity by Wells and Post (1958) (prior to the arrival of caustic method) one finds that slowly the tools became available to examine problems of running cracks as well as stationary ones under wave loading. In the earlier efforts much attention was spent on studying the speed of crack propagation and later the effect of crack speed on the distribution of stresses around the crack tip (Beebe, 1966; Bradley and Kobayashi, 1970; Wells and Post, 1958). Within the spatial and temporal resolution of the equipment available one found that the experimental measurements appeared to corroborate the computations based on the linearized theory of elasticity reasonably well.

Analytical Modelling

The mathematical analyses on which dynamic fracture work is principally based to date, originated with Yoffe's treatment of a crack (of constant length l) translating with velocity v (Yoffe, 1951). While not corresponding to a physically realistic situation, the solution nevertheless established the deviation of the dynamic stress field from the static one; because of the velocity dependence of the orientation of crack tip stresses it gave rise to the earliest "theory" for dynamic crack branching. Since then numerous solutions for stress fields at stationary and running crack tips have been published notably those by Broberg (1960) as well as Craggs (1960, 1963) who clarified the dependence of the magnitude of the crack tip stresses on the speed of propagation; other solutions were supplied by Ang (1960) for the suddenly appearing crack and with propagation (Baker, 1962) by Nilsson (1972) and by Achenbach for cracks growing after interacting with a stress wave (Achenbach, 1970a,b, 1972). A significant contribution to the determination of dynamic stresses at crack tips under general wave loading, including initiation and running of cracks was supplied by Freund (Freund, 1972a,b), followed shortly by a similar and supportive investigation by Kostrov (1975). These solutions are currently the analytical backbones of dynamic crack propagation in the absence of branching.

In addition to the limitation of dealing with crack growth in a straight line, a major shortcoming of current "closed form" analytical solutions is, of course, that they are not available for finite bodies, for the latter realistic boundary conditions must be satisfied if the solution is to parallel experimental investigations for times longer than the brief initial transients. In order to overcome that difficulty, researchers have started to employ finite difference (Kanninen and co-workers, 1979; Popelar and Gehlen, 1979; Shmuely and Alterman, 1973; Shmuely and Peri, 1980) and finite element analyses (Hodulak, Kobayashi, and Emery, 1980; A.S. Kobayashi, 1979; Nishioka and Atluri, 1982) which provide great flexibility for finite dimensioned geometries, and, in addition, accommodate with relative ease non-linear constitutive behavior. This observation is true whether one is concerned with the history of the stress state at a point - in particular in the crack tip vicinity - or whether one is interested in studying the development/application of path independent integrals (Atluri and Nishioka, 1983; Shih, 1984).

To summarize then our experimental and analytical capability in regard to studying dynamic crack propagation, we are able to characterize fairly well the elastic singular stress field at the tip of a stationary crack under wave impact or when the crack tip is in motion. The asymptotic stress field (K-field) for wave impact, for initial crack propagation as well as for non-steadily moving cracks in infinite media has been established (Freund, 1972,1974,1976); however, the time history of the spreading *stress field* associated with that intensity (away from the crack tip proper) is less well-understood, although efforts are under way to clarify that situation (Freund, 1983).

For cracks bifurcating dynamically in the infinite domain information is becoming available in the form of solutions for kinking or bifurcating cracks in Mode-III (Burgers, 1982; Burgers and Dempsey 1982; Dempsey, Kuo, and Achenbach, 1982; Freund, 1975) and for dynamic crack kinking in plane strain (Burgers ,1983). However, there is, as yet no analytical solution that parallels the experimentally achievable situation of inplane bifurcating crack paths. In addition, all these analyses suffer from the uncertainty regarding the physical conditions that lead to branching, so that the proper modelling for bifurcating cracks is still a cloudy issue. Recent experimental findings on this topic, discussed subsequently, offer a situation that does not appear amenable to attack in detail by the methods of "closed form" solutions in linear elasticity. The finite element method seems to hold considerable promise in principle. However, the expense associated with high resolution and accuracy/reliability of detail in the domain very near crack tip is still a major road-block to routine application of this numerical tool. For non-linear (plasticity) problems, it is even more necessary to provide the flexibility offered by numerical techniques to attack the real problems posed by the experimentalist in an effort to understand the processes that determine crack growth and branching phenomena. Although "closed form" analyses for elastic-ideally plastic behavior will fill a gap for some time, there is fertile ground for the scientific entrepreneur to cope with the economics of the predictive power of finite element analysis applied to dynamic crack propagation problems.

Experimental Tools

On the experimental side one is well able to record with moderate time and space resolution (2-5 μsec; 1 mm) stress fields that closely match the gross features of the stress field at the crack tip under transient conditions - notwithstanding some uncertainties to be discussed later. However, the spatial resolution does not yet appear to be sufficient to resolve the transient conditions at the crack tip where the physical non-linearities germane to the fracture process occur in a region smaller than one mm^2. Because of the duration of elastic sparks (Cranz-Schardin camera) or the limitations on spatial resolution, framing rate, etc., the events occurring within a radius of the crack tip of less than 0.1 mm are seemingly hidden from us for some time to come. However, it is precisely within this spatial domain that the physical processes controlling dynamic fracture occur within a very diminutive time scale. Unless either new or less expensive methods than the image converter principle with multiple (20-50) exposures become available, we need to *infer* what appears in this small, inaccessible fracture zone from accompanying phenomena. Thus, it is clear that a realistic interpretation of these phenomena requires an increased capability of dealing with the non-linear fracture phenomena at the crack tip. The exploitation of "closed form" solutions with somewhat idealized constitutive behavior will serve then an important role as a qualitative guide as well as a check on the validity of computational efforts.

Motivation for Dynamic Fracture Problems

We turn next to a summary of the more prominent issues in dynamic fracture mechanics. These are in the form of questions raised in the past as well as by some very recent observations resulting from comparatively detailed experiments on geometries well-understood by our present analytical (closed form) tools. About a decade ago increased interest developed in dynamic fracture as a result of concerns over nuclear reactor safety. This issue arose in connection with rapid cool-down of thick-walled steel structures and associated fracture propagaion of incipient flaws. The safety issue centered around both the initiation of crack propagation and the phenomena controlling arrest. In the latter context the interaction/competition between dynamic (inertia) effects and the toughness of the hotter material into which the crack would propagate was the motivating concern. Parallelling that engineering problem was and is the concern over dynamic fracture in long, pressurized (gas) pipe lines where both safety and replacement costs are important motivators for understanding control methods.

Many of the ensuing investigations followed closely fracture concepts and methods borrowed from quasi-static fracture mechanics. While it was well-recognized that wave phenomena were present and important, there was an *attempt* made to minimize the effect of dynamics by dealing with small specimens and to consider the dynamics of the situation as a small and possibly negligible perturbation on the static problem.

As a result of this viewpoint, much of the effort of understanding "dymanic fracture behavior" was really a search for understanding the elastodynamic stress field in particular test geometries. Clarifications to that end with the aid of photoelasticity (Bradley, Clark and Irwin, 1966; Dally, 1979; A. Kobayashi 1970; Riley and Dally, 1969) and through caustics (Kalthoff, Beinert and Winkler, 1977; Kalthoff and associates, 1980) clearly showed the time varying nature of conditions at the crack tip that are not in very good agreement with what should be called quasi-dynamic analyses for test situations believed to be analyzable from a static point of view. Another feature of the quasi-dynamic view point was the observation that only approximately half of the energy in a "dynamic" fracture experiment could be accounted for by the energy released to the fracture process, until Kobayashi, Emery and Liaw (1983) pointed out on the basis of finite element computations that all the energy can be accounted for when one considers that the total kinetic energy is trapped in the specimen, but does not directly and immediately participate in the crack tip fracture process.

Several problem areas can be distilled out of this background: To each there exist partial answers on the basis of past work, but in each there seem to be more questions than answers. It is, perhaps, logical, certainly easiest, to group these various areas of interest into the categories:

Initiation	Branching
Propagation	Arrest.

While arranging the following discussion in this way it should be recognized that the intent in this exposition is a review of the more "fundamental" aspect of dynamic fracture processes. The motivation for these studies derive from diverse engineering problems of serious concern which relate to the need for both fracture prevention as well as fracture promotion.

In the latter category we find the problems of comminution: these are of interest in the pharmaceutical and in the chemical engineering industry where generating small particles in an energy efficient way is important. On the macroscopic scale the technology of developing cracks and "porosity" in geological formations for improving recovery of oil, natural gas or thermal energy draws on the results of dynamic fracture research.

In the more preventive vein of designing *against* dynamic fracture the need exists to understand the propagation of cracks in pressurized gas pipe lines as well as their behavior in structures such as ships or large rocket motors. There, as in pressure vessels for nuclear reactors, both the conditions leading to crack initiation, growth and arrest need to be understood in order to minimize risks. In addition to these typical crack propagation problems those connected with projectile penetration of rock or metal targets are important. Moreover, there are many situations where post mortem evaluation of an accomplished failure is important in analyzing the source and process of a failure in an engineering structure in order to prevent a failure recurrence through design improvements. In these latter cases the fractography of dynamically generated fracture surfaces is of prime importance.

It is clear that such a broad range of problems generates an equally broad spectrum of needs and questions. For convenience of discussion purposes, these may be divided into design oriented needs on the one hand, and understanding of basic phenomena on the other, even though all serve to enhance our ability to cope more effectively with the problems of prevention or promotion of (dynamic) fracture.

For design purposes it may be necessary to draw on limited available information which serves to construct relatively simple theoretical concepts. Such situations arise often in connection with engineering analyses. Simultaneously one needs to develop additional knowledge on a somewhat short term basis (advancing engineering concepts), yet fully recognizing that a still more satisfactory resolution of important questions must await answers from long range research which are geared to clarify the fundamental phenomena. Within this spectrum of concern with detail and investigative sophistication this presentation is structured to emphasize the more *fundamental aspects of dynamic fracture* rather than those of immediate engineering concern, although the awareness of the latters' importance is clearly the driving force behind the following discussions.

INITIATION RESULTING FROM STRESS WAVE LOADING

In most investigations to date loading on test geometries is accomplished in one of basically two ways: By applying the load suddenly to a geometry containing a sharp preformed crack or by statically loading a geometry containing a *blunt* crack-like discontinuity which is suddenly externally sharpened by an impacting device. Both methods are basically mechanical devices for which timing precision is in the msec range while the ensuing crack propagation phenomenon falls in the μsec or tens of μsec range: It is impossible to study the onset of crack growth under such a time-imprecise initiation mechanism with cameras geared to framing rates on the order of 10^5 to 10^6 frames per second with only a small number of exposures. Rather recently, Dally and Shu (1979) have resorted to a clever choice of test specimen shown in Fig. 1 in which the rupture of the ligament at A could be used as a trigger for camera operation to study the onset of crack propagation at B. While this method can be well synchronized and calibrated to investigate crack initiation from wave action (a sudden unloading wave from the ligament rupture to the crack tip) this capability has not yet been exploited systematically.

In this connection it is interesting to point out that when the crack starts to propagate - postinitiation - the stress intensity factor drops as a result of the local unloading process (Dally and Shukla, 1979; Freund, 1983; Ravi-Chandar and Knauss, 1981). We shall return to this phenomenon in the next section in connection with the recording of crack tip stresses for running cracks under transient conditions.

Dynamically induced crack growth can be considered either as a problem of crack generation or, alternately, one of growth of a pre-existing crack. Researchers at the Stanford Research Institute International in California (Seaman, Shockey, and Curran, 1973; Shockey, Kalthoff, and Erlich, 1983; Shockey, Seaman, and Curran, 1979) have studied the initiation of small cracks in macroscopically continuous materials under very short duration stress pulses. These were generated in plate-impact experiments and produced pulses up to 40 Kbar (about 6×10^5 psi) for a duration of about 1/5 μsec, resulting in average strain rates of about 10^5/sec. One finding of these investigations was that cracks with a wide distribution of sizes are generated which develop from an equally wide distribution of inherent flaws in the material. From the spatial distribution of these cracks and from a knowledge of the stress history at every point along with model computations it developed that the rate of growth of nucleated cracks was proportional to their size so that a "viscous" growth law seemed to apply (Seaman, Shockey, and Curran, 1973). This result is of direct interest where fragmentation or dynamic comminution is concerned. It is also important in connection with initiation and propagation of macroscopic, pre-existing cracks inasmuch as the material at the tip of a macroscopic crack under dynamic loading is likely to experience similarly high stresses and loading rates (Shockey, Seaman, and Curran, 1977). We shall indeed see later that the tip of a running crack exhibits multiple micro fractures which are responsible for the rough appearance of the fracture surfaces. However, establishing "analytically" a quantitative/qualitative relationship deduced from a spatially distributed ensemble of micro cracks around the crack tip has not been attempted. Therefore, a more definite understanding of *how* this nucleation process controlls initiation and propagation of cracks is not well understood, if at all.

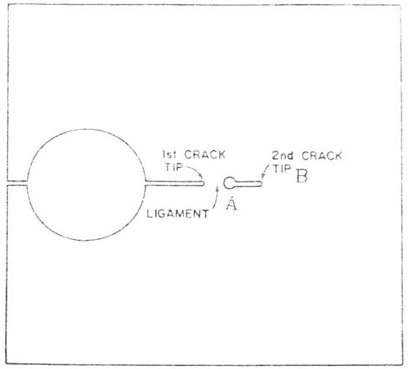


Fig. 1. Modified compact tension specimen used to study the dynamics of crack initiation. (According to Dally and Shukla, 1979.)

A more direct examination of crack growth initiation *from a preexisting crack tip* under stress wave loading was conducted by Smith and Knauss (1975) on large plates of Homalite 100 with the help of an electro-dynamically induced pressure on the crack surfaces (cf. Fig. 2 for loading arrangement). Freund's solution for the semi-infinite crack together with the known stress pulse history applied to the crack surfaces was used to compute the stress intensity factor at initiation; the instant of initiation was determined experimentally with the aid of high speed photography. In spite of some uncertainty at that time about the calculated stress intensity factor, it was clear that at very short times on the order tens of microseconds substantially higher stress intensity factors are required for crack initiation than under quasi-static condition. Repeat tests on Homalite 100 by Ravi-Chandar and Knauss (1982a), now using caustics to assess the stress intensity factor, brought numerical changes but confirmed the sharp increase in stress intensity required for crack initiation when fracture occurred at times shorter than 50 μsec (for comparison note that the shear wave velocity $\doteq$ 1mm/μsec).

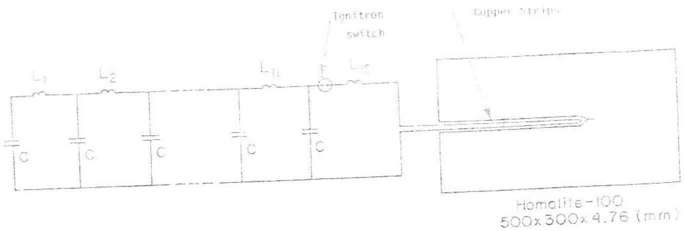


Fig. 2. Electromagnetic loading scheme and specimen configuration. (Ravi-Chandar and Knauss, 1982a).

Drawing on the earlier experiments on crack nucleation and growth at SRI International, Kalthoff and Shockey (1977), as well as Shockey, Kalthoff and Erlich (1983) have investigated conditions that determine when (small) pre-existing cracks begin to grow under short term (20 to 80 μsec), highly intense stress pulses. Because there was no possibility of recording the fracture process directly their results are presented in terms of growth dependence on initial crack size rather than as a time history of the crack tip loads and associated crack propagation history. The results of those investigations are summarized in Fig. 3 as a proposed instability surface (the test material is different from that used in the Caltech study so that a direct comparison is difficult). The studies at SRI International showed that for crack growth to occur the stress pulse must act for a certain minimal time. This observation is consistent with the notion suggested in 1971 by Steverding and Lehnigk that fracture initiation might be governed by the need to achieve some minimum "impulse" (of the "crack extension force"). In principle, the impulse law in classical mechanics deals only with the velocity changes of masses subjected to force(s). Whether an "impulse criterion" in fracture has meaning in that sense is questionable. In the fracture problem the behavior of the material must enter the considerations either through the

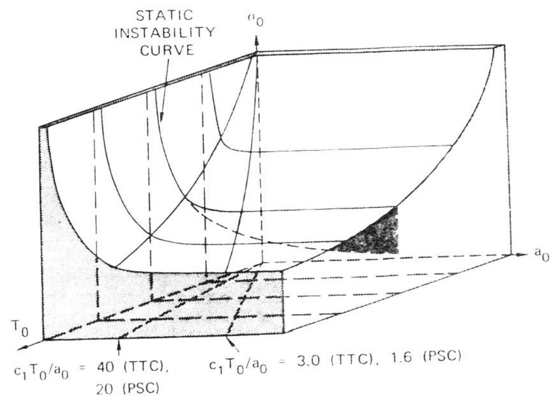


Fig. 3. Crack instability surface for penny-shaped cracks (PSC) and through thickness cracks (TTC) according to dynamic minimum time-stress intensity criterion. (From Kalthoff 1983.)

finite size of the damage zone associated with any crack tip fracture process or through the rate dependence of material behavior *per se*.

That a minimum time should be involved in *real* fracture processes may be seen from simple considerations. A finite time is always required to attain a stress over a sufficiently large domain in the crack tip area for frature to occur. If one considers that for a large crack (no interaction of the two crack tips) the stresses at the tip rises under step pressure p_o according to $\sigma_{22} \sim P_o(t/x)^{1/2}$ then achieving a critical stress $\sigma_{22} = \sigma_c$ out to a distance $x = \alpha$ requires $P_o \sim t^{-1/2}$, provided $\alpha << tc_s$ with c_s the shear wave velocity. For Homalite 100 c_s is close to 1 mm/μsec. Thus, if α = 0.1 mm, times larger than 1 μsec would qualify. By this argument fracture could start if the stress intensity factor attains a critical value *and if the time exceeds such a minimum time*.

In fact matters are not quite so simple. In Fig. 4 are shown results for fracture initiation (Ravi-Chandar and Knauss 1982a) which indicate that the stress intensity required for the beginning of crack growth in Homalite 100 rises sharply for times less than 50 μsec, which is large compared to the earlier estimate. Thus considerations other than merely elastic wave propagation must be important. Another estimate for the crack initiation time can be made in terms of a (quasi-static) viscoelastically controlled crack opening displacement (Smith). If one assumes a viscoelastic power law for the creep compliance, i.e. $D(t) = D_o t^r$ (Ravi-Chandar and Knauss 1982a) and denotes by K_{IC}, the stress intensity factor for quasi-statically induced crack propagation and c, some constant, then the initiation time is given by

$$K_{const} = K_{IC} + \frac{c}{t^r}. \quad (1)$$

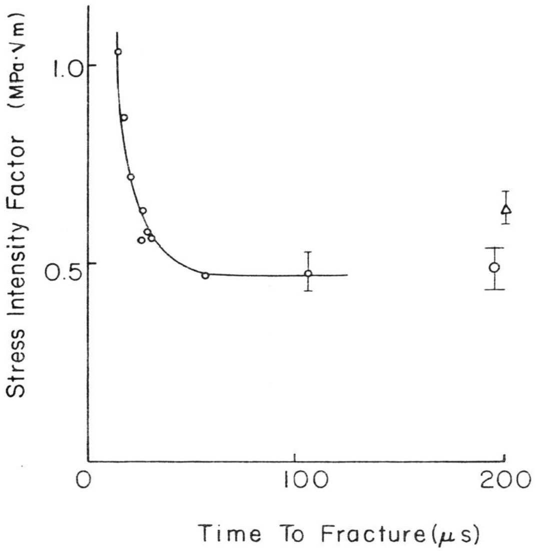


Fig. 4. Variation of the stress intensity factor required for initiation with the time to fracture. (Ravi-Chandar and Knauss, 1982b.)

Upon replotting the data in Fig. 4 as in Fig. 5 on a log-log basis, one finds that a value of r = 2 fits the data quite well although this value is large for linearly viscoelastic behavior; of course, one would not expect such linear material behavior to apply in this situation anyway.

From these simple considerations one deduces that the time scale of fracture initiation is not principally governed by the time required to establish an elastic stress field in the diffraction process but by a larger time scale commensurate with "viscous" effects. To say whether the latter is of a material intrinsic nature (viscoplasticity) or of the type encountered through the crack nucleation by Seaman, Shockey, and Curran (1973) in the formation of the crack tip damage zone would be speculative at this time.

It is also well to remember that if crack tip displacements are involved in allowing crack initiation to occur (COD) that the time history is not the same as for the stress intensity factor (Thau and Lu, 1971), displacements being approximately proportional for short times to the first power of time while the stress intensity grows as $t^{1/2}$. However, the timescale for establishing the elastic displacement field is on the same order as that for the stress field so that consideration of displacements rather than stresses will hardly account for the large time discrepancy mentioned.

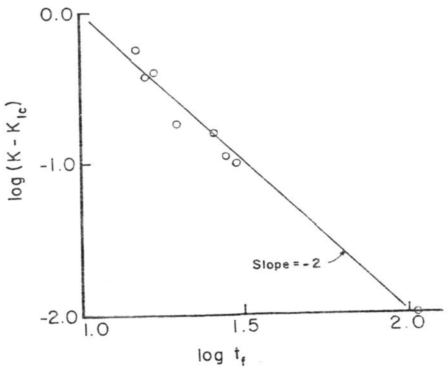


Fig. 5. Logarithmic plot of the data in Fig. 4. (K_{Ic} is the quasi-static critical stress intensity factor and t_s is the time at fracture initiation. (From Ravi-Chandar and Knauss, 1982b.)

CONTINUOUS CRACK PROPAGATION

In this section we discuss problems of crack propagation after the initiation phase but before possible branching occurs. We discuss first the effect of crack initiation on the stress intensity field when the crack begins to run.

It is commonly accepted that the stress intensity factor determines crack growth behavior and that the associated "singular" stress field is well established, i.e., it extends to a distance from the crack tip the size of which is usually gaged in terms of static stress analyses. This consideration is very important when information is gathered at the crack tip over a wide domain such as in the photoelastic method (domain on the order of cm). When transient conditions arise such an assumption may not be, and usually is not, valid.

Inasmuch as the stress relief *during* crack initiation constitutes a highly transient event, the question arises as to how long a time span is required after initiation before the "singular" stress field at the moving crack tip extends over a reasonably sized domain. Following the absence of a stress drop after initiation in recent experiments on crack initiation and propagation at high stress rates (Ravi-Chandar and Knauss 1983) Freund has computed the time scale for establishing the singularity field (Freund 1983). Of the two examples presented to date, let us consider one of these here.

A semi-infinite crack in an infinite plane is subjected to a uniform pressure step loading at time t=0. At a time t_o later the crack begins to grow with constant speed v. The pressure continues to act only over the originally pressurized surfaces and does not follow the crack tip. Drawing on earlier results (Freund, 1973), the stress at some fixed distance β ahead of the moving crack tip is examined by calculating the crack-normal stress S_{22} on the crack axis. That stress should be less than the value attained after the initiation transients have died out and steady crack propagation conditions have been achieved.

Let the steady stress field (stress at $x = \beta$ ahead of the tip) be characterized by $S_{22} = K(t)(2\pi\beta)^{-1/2}$. Using properties and measurements for Homalite 100, and for t_o = 50 μsec Freund computes the ratio $S_{22}(\beta,t) \cdot (2\pi\beta)^{1/2} / K(t)$ as shown in Fig. 6. One notes that (for Homalite 100) it takes 80 μsec after initiation for the stress at $x = \beta = 2$ mm to attain 95% of its value for steady crack propagation (dilatational wave speed $c_1 = 2\text{mm}/\mu\text{sec}$) while it takes 400 μsec to achieve the same relative state at $x = \beta = 10$mm ahead of the crack. During this time the crack has moved on the order of 30 and 150 mm, respectively. Recalling that high speed photographic time resolution is fairly standard in the 3 to 10 μsec range, it is clear that these times are surprisingly large.[1] In fact, in small specimens a substantial portion of the crack propagation history can be taken up before a "steady" crack propagation stress field is established, especially if photoelastic data is involved.

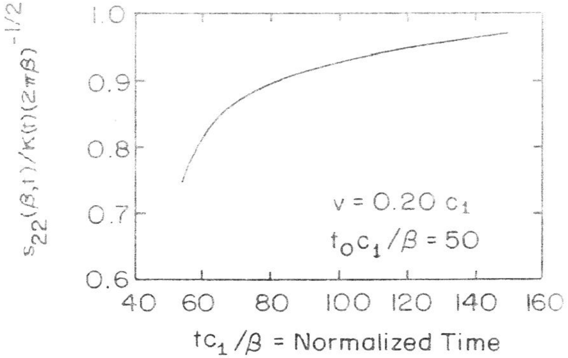


Fig. 6. An example of the ratio of traction on the prospective fracture plane at a fixed distance ahead of the moving crack tip to the traction due to the singular solution alone versus time for dynamic crack growth with transient loading. (Freund, 1983a.)

For metals this time scale would be shorter because of the higher wave speeds. However, since reflections of waves at the boundaries give rise to transients at the crack tip, small specimens may inherently lead to uncertainties in measured stress intensities (even metal specimens). There may still exist a problem even in the event that caustics are used which gather information from a much smaller domain about the crack tip than the photoelastic method because (cf. Figure 6) for $\beta = 2$ mm (radius of initial curve for a caustic) a time of about 30 μsec is required to achieve 90% of the stress intensity field 2mm ahead of the running crack. Thus much more careful data analysis is necessary than has been practiced in the past, but the details in terms of Freund's analysis need yet to be worked out. In discussing the following findings we need to be mindful of these uncertainties.

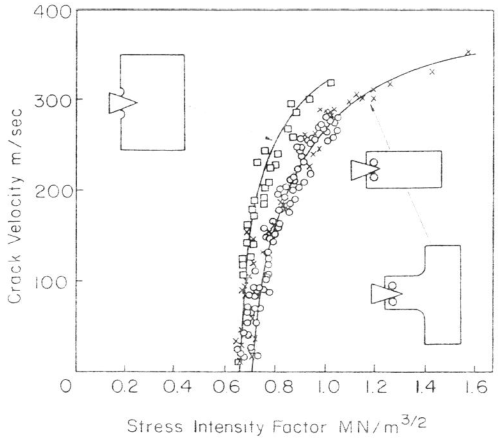


Fig. 7. Velocity and stress intensity factor for different specimens of Araldite B (Kalthoff 1983).

1. For achieving only 90% equivalence, these times change to 30 and 150 μsec, respectively; distances travel by tip are 12 and 60 mm, respectively.

Crack Speed and the Stress Intensity Factor

Perhaps the (experimental) observation which has dominated most of the thinking on dynamic fracture during the last decade or two is that cracks tend to propagate at different speeds depending on the stress intensity factor. This observation has been made both on polymers (Homalite 100, Araldite, PMMA) (Dally, 1979; Kalthoff, 1983; Kalthoff, Beinert and Winkler, 1977; Kobayashi and Mall, (1978); Kalthoff and associates, 1980) and on metals (Kanazawa and co-workers, 1981; Rosakis, Duffy, and Freund, 1983; Shockey and colleagues, 1983). It is generally recognized that cracks propagate at "maximal speeds" which are a fraction of the Rayleigh surface wave speed (about one half or less of it) provided the stress intensity is high enough and branching does not occur. For stress intensities below that which causes "maximal" speed, the crack propagates more slowly, such that at stress intensities near the lower limit for propagation the crack velocity changes drastically with small changes in stress intensity (cf. Fig. 7).

Usually, the experimental scatter in determining either the crack tip stress state or the velocity is sizeable so that it is not easy to establish a definite relation between the stress intensity factor and the velocity. Although different test geometries and load histories tend to produce different functional relations between the stress intensity factor and the velocity (see e.g. Fig. 7 based on data reported by Kalthoff (1983)) there are supporters for the idea that the velocity is a unique function of the instantaneous stress intensity factor (Dally 1979; Dally and Shukla, 1979; Irwin and co-authors, 1979; T. Kobayashi and Dally, 1977) and those who have consistently questioned the generality of such a relation (Kalthoff, 1983; A. Kobayashi, 1983). The doubt stems from a systematic, though small, difference between such relations that result from different types of test specimen geometries while the support comes from the uncertainty of the whole data set due to the data scatter - as well as a hope that mother nature favors a simple state of affairs so that we mortals can "understand easily."

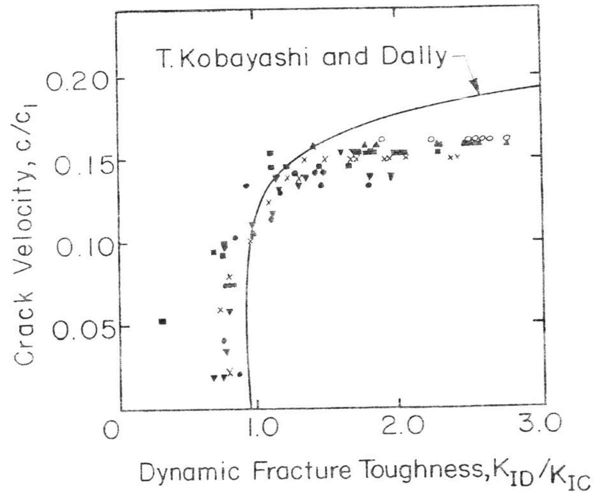


Fig. 8. Smoothed-crack-velocity vs. dynamic-fracture-toughness relations of single-edged-notch Homalite-100 plates. (Extracted from Kobayashi and Mall, 1978.)

The proposition that the instantaneous stress intensity factor produces a unique value of crack propagation has been established by analytical *and* experimental means only for a viscoelastic material in the absence of any dynamic effects (Knauss, 1973; Mueller and Knauss, 1971). But even here, such a unique relation exists only in the absence of "strong transient" loading (Knauss, 1976), so that there exists no universal or unique relation between the *instantaneous* rate of crack growth and the *instantaneous* stress intensity factor for this particular class of time dependent materials.

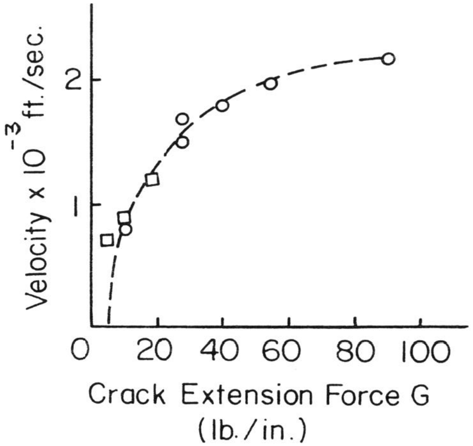


Fig. 9. Crack extension force, G versus constant section velocity, V_c. (Extracted from Paxson and Lucas, 1972.)

Returning now to the elasto-dynamic problem, the lack of certainty about or applicability of a unique K-v relation, as it is often called, is accentuated by a paucity of data on a variety of materials. It might well be that for some materials such a relation may be more reasonable than for others.

However uncertain the proposition may be that there exist a material function between the stress intensity factor and the instantaneous velocity there is something to be learned from these K-v curves. They have been obtained for several clear polymers as well as for structural steels: As is evident from Fig. 7 to 11, the general behavior is *very similar, including the fact that the "maximal" speed is on the* order of 1/2 or less of the Rayleigh surface wave speed. One would argue, therefore, that the basic physical processes that control fracture in all these materials are essentially the same or at least very similar. Moreover, this observation is a strong motivation for investigating some dynamic fracture problems with simulation materials such as optically clear, brittle polymers which are more convenient to use in the laboratory than engineering metals.

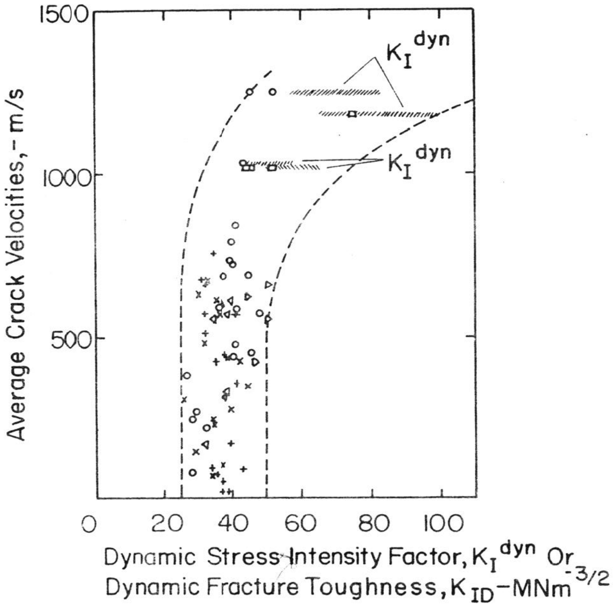


Fig. 10. K_I^{dyn} and K_{ID} values as a function of crack velocity in steel. (Extracted from Shockey and co-workers, 1983.)

In his work on inorganic glasses Shardin (1959) and his co-workers had noted that cracks tend to travel at a constant speed. He also observed that under static far field loading, cracks would accelerate - in his experiments over an interval on the order of 15-20 μsec - but that with increased applied stress the length of this acceleration phase decreased systematically[2] until it was difficult to discern within the time resolution of his equipment (3 μsec) (cf. Fig. 12).

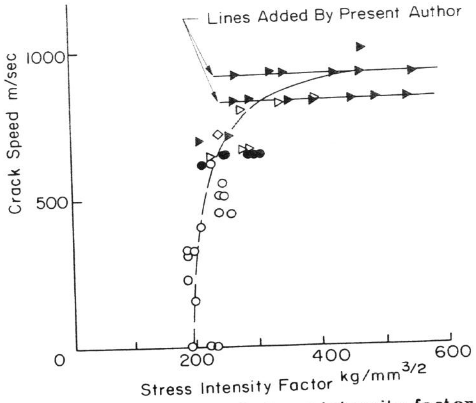


Fig. 11. Velocity and stress intensity factor for KAS steel. (Extracted from Kanazawa and co-workers, 1981.)

In working with Homalite 100 Beebe (1966) loaded large plates in tension with an air piston; loading rates were in the millisecond time frame (fast, but not really stress wave loading). He found that the crack would accelerate smoothly to a terminal velocity (cf. Fig. 13). This acceleration behavior might well lead one to consider a dependence of the crack velocity on the instantaneous stress intensity factor (Beebe did not record the stress intensity history). Nor did Beebe's apparatus allow a wide range of loading rates so that a systematic and more extensive study of the crack acceleration phase was not possible. But, if the "brittle" fracture of Homalite 100 mimicks fracture of inorganic glass, as studied by Schardin, then an increase in loading rate should also shorten the acceleration phase.

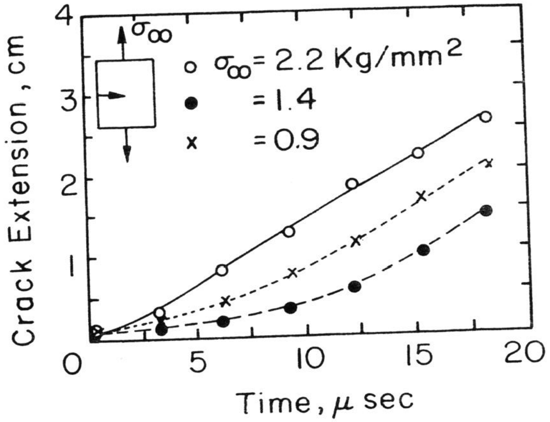


Fig. 12. Crack acceleration in PMMA. (Data of Schardin, 1959.)

In fact measurements (Ravi-Chandar and Knauss, 1983a) made under stress wave loading (cf. Fig. 2 for experimental arrangement; time scale ~ 20 μsec, i.e. much shorter than Beebe's tests) show that within a time resolution of 5 to 10 μsec an acceleration does not exist and the crack will start off with a fixed velocity. (cf. Fig. 14, for example). What is, perhaps, more surprising is that *the crack propagates thereafter at a constant velocity even when the stress intensity factor varies over a considerable range*. It thus appears that the initial (high rate) conditions determine the crack tip damage. This crack tip damage in turn controls the time scale of its propagation with a low sensitivity to changing crack tip stresses.

2. Anticipating the later discussion on crack arrest Schardin also noted that cracks would always arrest abruptly and never to undergo a deceleration phase.

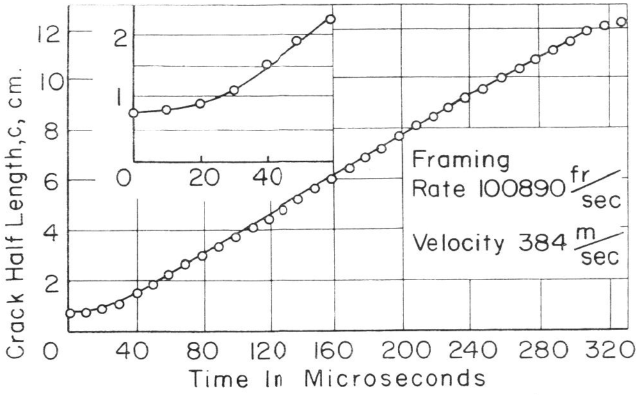


Fig. 13. Crack acceleration in Homalite 100 at 24°C. (Data of Beebe, 1966.)

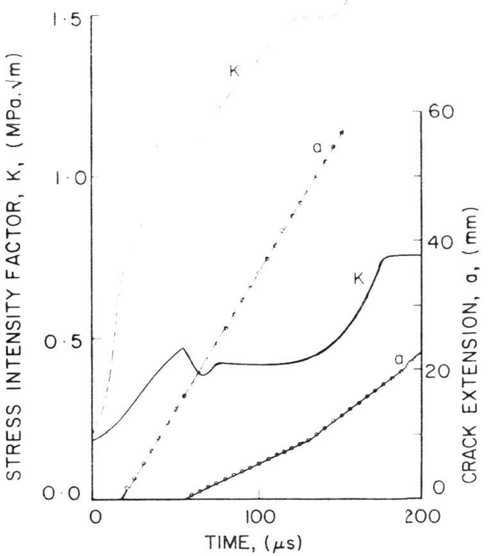


Fig. 14. Stress intensity factor and crack extension history in Homalite 100 (Ravi-Chandar and Knauss, 1983a).

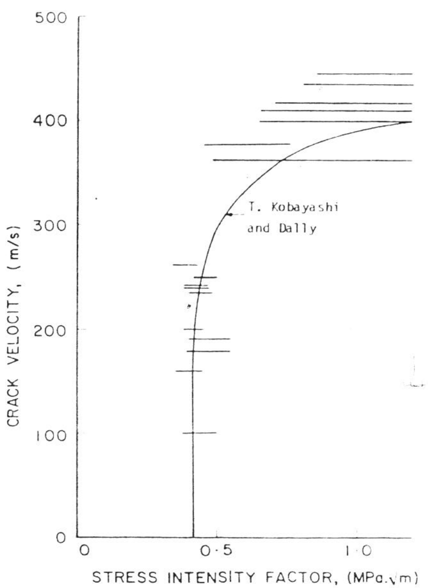


Fig. 15. Crack velocity versus instantaneous stress intensity factor in Homalite-100. (Ravi-Chandar and Knauss, 1983a.)

The crack changes velocity only through interaction with a significant stress pulse such as occasioned by a tensile wave, and then only if the crack speed is not already close to the "terminal" speed in which case branching may ensue (Ravi-Chandar and Knauss, 1983a). Data from these experiments are shown in Fig. 15 together with an average "K-v curve" for the same material. The horizontal lines indicate the variation of the caustic-measured stress intensity while the crack maintained constant speed. Note that crack propagation occurs at velocities distinctly higher than the "terminal" velocity achieved in small specimens loaded by slower, more conventional means.

Thus a rather complicated crack propagation behavior emerges which is strongly dependent on the initiation conditions. Quasi-statically induced fractures such as occur in most test situations investigated to date can accelerate their velocity in some relation to the increasing stresses at the tip. This crack acceleration is possibly a function of the rate of change of the stress intensity factor - not merely because of truely viscous material effects - and not only a function of its instantaneous value. The crack accelerates to a "terminal" velocity if the specimen is large enough unless additional wave interactions occur at the crack tip.

However, if the crack motion is initiated very rapidly by wave action the crack will propagate (almost) immediately with a constant velocity which increases only if a stress pulse impacts on the running crack tip. It appears that stress pulses with a rise time less than 15 μsec are required to effect a change. In this way velocities in excess of "terminal"velocity normally reported can be achieved before bifurcation or branching occurs. Velocity reductions, other than arrest, have not been observed in our experiments on Homalite 100. Thus the concept of a unique relation between an instantaneous crack velocity and stress intensity factor is highly questionable at best. The problem of crack speed seems to be inextricably involved with the test geometry and the related wave reflection history.

These phenomena are not confined to Homalite 100. Schardin presents data on plexiglass (cf. Fig. 16, Schardin 1959) in which a sudden change in velocity occurs, which appears to coincide with the reflection of the Rayleigh wave from the boundary of the small specimen. Moreover, data on Araldite B presented by Kalthoff (1983) indicates the same effect noted in Fig. 15 (cf. Fig. 17). The stress intensity factor changes by more than a factor of two while the crack velocity remains constant. There are similar indications for the velocity constancy in the data of Kanazawa and co-workers (1981) represented in Fig. 11 where the same velocity is associated with a large range of stress intensities. Clearly there is a need to examine this phenomenon carefully in other materials. If borne out in other solids, specifically in structural metals, these results have serious implications for using current test data to make failure prediction in structures subjected to wave loading; this aspect will be discussed in more detail in the last section.

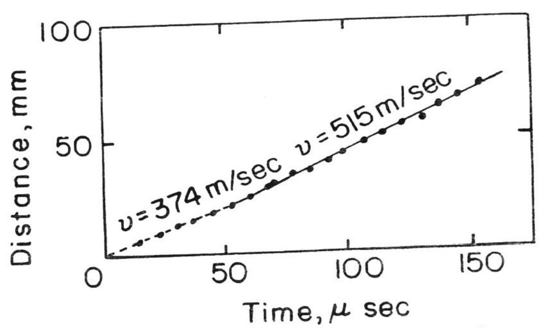


Fig. 16. Traveling fracture in plexiglas. (From Schardin, 1959.)

Microfracture at the Crack Tip

In order to learn more about the process of dynamic fracture, one can examine the appearance of the crack tip for steadily propagating cracks by real time photography. Figure 18 shows three views of crack tips in Homalite 100 in a direction of 45% relative to the crack plane. The three views correspond to growth under low, medium, and high stress intensities, where the latter was such that branching was imminent. For all three photos the crack velocity was nearly the same. In terms of surface roughness, they correspond to regions normally referred to respectively, as mirror, mist, and hackle. The field of view for these photographs was about 8 mm; with a crack speed on the order of 400 m/sec the capturing of these events required several tests in order to capture the event through this narrow time and space "window".

In Fig. 18 a one sees clearly the typical "thumbnail" shape of the crack front that is characterstic of slow (fatigue) or quasistatic fracture. The shadow bulges at the intersections of the crack front with the plate surfaces are caustics. At the higher stress intensity associated with Fig. 18b one observes scalloped shadows which are each caustics resulting from individual local fractures ahead or at the front of the common "crack tip." In Fig. 18c these individual fractures are more pronounced (larger) and there are fewer of them; the large caustics at the crack-plate surface intersection indicate the higher stresses as compared with Fig. 18a and b.

These figures verify through direct observation that crack growth occurs through an ensemble of micro-cracks which advance the main crack through coalescence. Thus crack growth at high "stress intensity" (high speed) really occurs by the propagation of an ensemble of micro cracks. At low stress intensity factors the individual cracks are, presumably, too small to be resolved by the photographic recording method and accordingly the crack front appears smooth and crisp (Fig. 18a).

When microcracks nucleate at the crack front - in the sense of the work of Seaman, Shockey and Curran (1973) - unloading waves are radiated from these sites which appear often visible as circular wave patterns around but continuously displaced from the crack front as, for example, in the case of a high strength steel in Fig. 19 (Shockey and co-workers, 1983). The translation of the centers of the stress wave circles (nearly circles) and the difference in the circle radii suggest that the waves travel with the shear wave velocity (about twice the velocity of crack propagation). These radial waves are more frequent and more pronounced in metal fracture. Besides indicating clearly that dynamic metal fracture occurs also by the propagation of cracks ensembles this observation raises question of whether the size of the micro cracks tends to be larger in metals. However, it is more likely that the stronger signal is simply due to the higher energy levels involved.

Because the micro cracks do not occur all in the same plane but are spatially distributed around the "tip" their coalescence produces a rough surface. If one takes the maximum depths of the fracture surface makings as a measure of the roughness - and possibly as a measure of the size of the process zone - one finds with the help of a light section microscope that the roughness increases continuously with the stress intensity factor. As illustrated in Fig. 20, the roughness in Homalite 100 varies with a high power (11th power) of the instantaneous stress intensity factor (Ravi-Chandar and Knauss, 1982c). It is clear that the energy required for this process increases tremendously when high crack tip stresses are achieved. It should be emphasized that this increase in fracture energy is to be considered the result of high stresses (high stress intensity) and not the result of some inherently "viscous" material behavior in conjunction with the high velocities that are normally associated with high stress intensities. This latter association of the fracture energy with velocity is

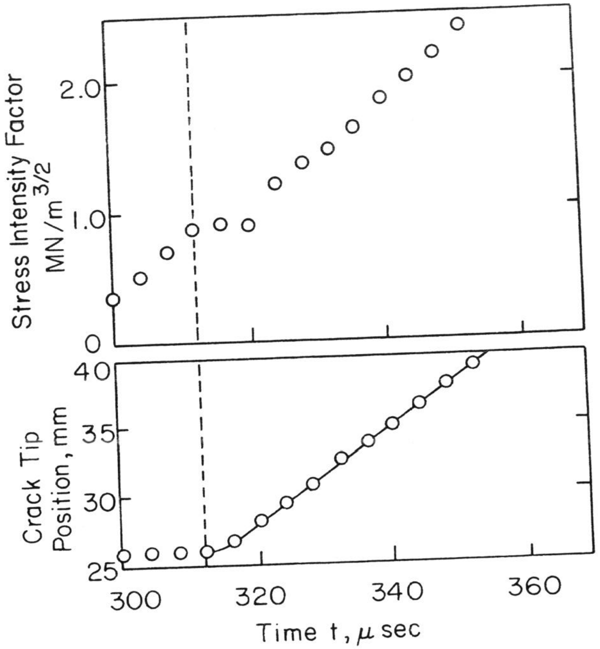
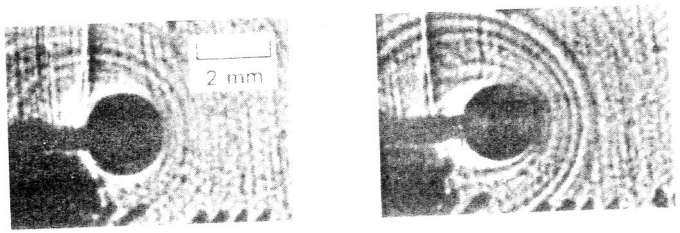


Fig. 17. Stress intensity factor history and constant crack speed (Kalthoff 1983).

Fig. 18. High speed photomicrographs of the crack front in the 'mirror', 'mist', and 'hackle' zones (Ravi-Chandar and Knauss, 1982c).



16 μs 24 μs

Fig. 19. Shear waves radiated from the running crack tip (Shockey and co-workers, 1983).

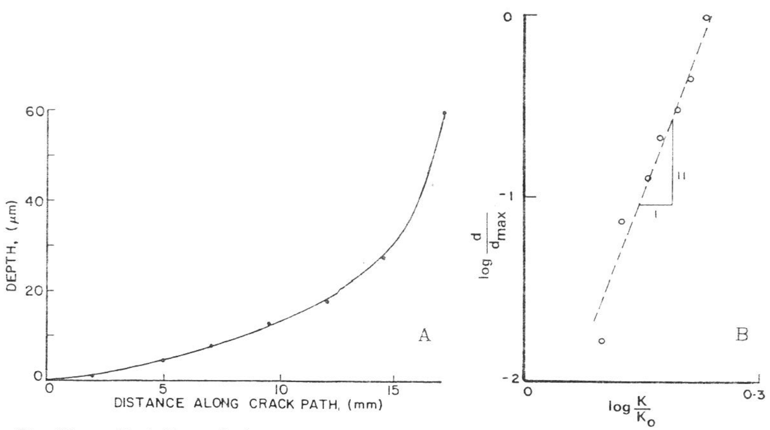


Fig. 20. Variation of the size of the fracture process zone with crack extension and stress intensity factor (Ravi-Chandar and Knauss, 1982c).

often made in dynamic fracture work to "explain" why crack propagation does not follow the idealized analytical predictions. If there existed a unique relation between stress intensity and crack velocity such a distinction would be immaterial. However, inasmuch this unique relation does not exist as indicated above a dependence of the energy on the stress intensity (history) may be, conceptually, of fundamental importance.

Source of Crack Speed Limitation

One of the as yet unexplained phenomena in dynamic fracture is the limitation of the maximal crack speed to values considerably less than the theoretically admissible Rayleigh surface wave speed. The most common "explanation" offered is that the energy required for fast crack growth increases with speed and a balance between the energy release rate and the energy available can only be established at an appropriate value of crack velocity. Such an argument begs the question because the laws of thermodynamics are always obeyed and provide no sufficiency test for a process to occur.

It seems more profitable, therefore, to look for an explanation in the more detailed physical processes occuring at the crack tip. For example, Broberg (1973) has examined, in a somewhat idealized model, the effect of the reduction of wave speeds through plastic deformation at the crack tip and finds it to have a marked effect on the crack tip stress field. In particular he finds a reduction or elimination of a singularity type field which is consistent with a spatially diffuse fracture process rather than a point-localized one associated with a singular field.

In a way Broberg thus models some aspects of the physical process discussed here. In terms of the multiply nucleated cracks at the tip as illustrated in Fig. 18 it is clear that their growth and coalescence cannot be mutually independent of each other. The influence of the dynamically induced stresses due to the generation and growth of one micro crack on every other neighboring one occurs via stress waves. This process requires time more than simple wave propagation. One should, therefore, hardly expect the speed of crack propagation to be determined by the dynamics of the (continuum) stress field at the crack tip but rather by the dynamic interaction of the micro cracks in the process zone. That this interaction process can readily account

for the significantly lower values of crack speeds when compared with wave propagation speeds is readily apparent. We need only consider qualitatively that if, for example, micro cracks separated by the size of a process zone need to "communicate" only twice before the process zone can advance by its own length, then the crack advance can occur at most at half the shear wave speed. Moreover, we remember from Figs. 18a and 18b, and 20a and 20b that at relatively low stress intensity the separation of microfractures is very small (mirror zone) but increases dramatically with stress intensity factor. One should expect therefore that with increasing stress intensity, the delay caused by interaction of the microcracks in the process zone should also increase markedly, i.e. *the discrepancy between the ideal theory* (rate-independent, constant fracture energy) *and experiments should increase dramatically* with increasing stress intensity. This observation is illustrated in Fig. 21 (Ravi-Chandar, 1982), where, notwithstanding, the uncertainty about its uniqueness validity mentioned earlier, the experimental data for the K-v relation (T. Kobayashi and Dally, 1977) have been used. The "theory" assumes that the speed is controlled entirely by kinetic effects, with the fracture energy remaining constant for all velocities.

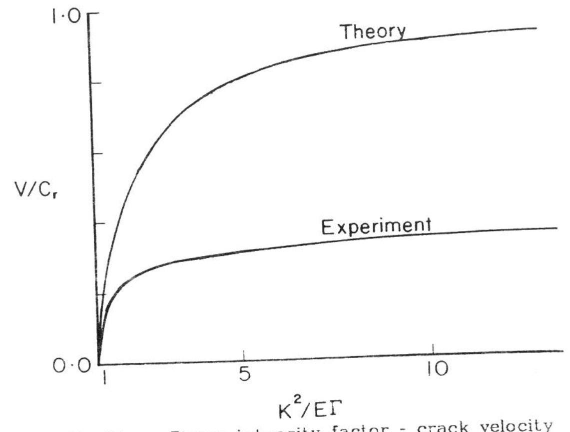


Fig. 21. Stress intensity factor - crack velocity relationship (Ravi-Chandar, 1982).

It should be clear that for such a speed controlling mechanism to be effective it is not necessary that every micro fracture along the crack front (parallel to it) be influenced by every other one through wave interaction. Rather it may be only necessary that for regions along the crack front some spatially limited interaction exists which allows the gross crack to propagate more or less as a line. Such a process would make the growth of cracks at high stress intensity a truly three-dimensional phenomenon, even though the crack may propagate in a thick plate under a macroscopically two-dimensional stress field.

This concept is important in understanding the transition of fast fracture to branched cracks which will be discussed in the next section. In the context of the present dicussion of the importance of the ensemble of microcracks we may consider their generation at elevated stress intensity to occur spatially separated along the crack front over distances that are equal to or larger than the dimension of the process zone in the growth direction. Under such conditions the micro fractures can become largely independent of each other along the crack front and the possibility exists for groups of them to establish their own growth pattern without interconnecting to form the major crack. That process leads to branching and terminates the growth of fracture as a single macro crack. We proceed now to discuss the phenomenon of branching as a natural outgrowth of the crack propagation process through an ensemble of micro cracks.

CRACK BRANCHING

The division of a single crack into two (or more) dynamically propagating branches has been observed quite early (Smekal, 1936; Schardin, 1959) but has eluded a truly satisfactory explanation in terms of either analytical foundation or in terms of a physics-based criterion. Yet, in part because of its importance in problems of comminution, in part because of the scientific challenge to understand the physical processes leading to fracture, branching has invited a continuously active investigation.

The earliest analytical attempt at explaining the phenomenon on purely continuum mechanistic grounds by Yoffe (1951) is today no longer accepted, primarily because

a. the predicted branching angle is uncharacteristically large,

b. physically, branching occurs at velocities substantially below that at which the stress field could "favor" branching, and

c. the stress, circumferential to the crack tip and ostensibly responsible for causing crack path alteration at or above a certain speed, is not a principal stress as it should be (Baker, 1962)

Nevertheless, the idea that branching is a phenomenon dependent on the crack tip velocity through material inertia has long persisted - and still does persist. There is increasing evidence, as discussed at the end of the previous section, for example, that while branching is only observed at high crack propagation speeds (other than in corrosion problems and in some highly filled viscoelastic polymers) the ***velocity aspects are an adjunct to the branching phenomenon*** rather than the driving factor. This idea has been mentioned in the literature before. For example, in 1972 Congleton suggested that "... the redistribution of the stress field ahead of the moving crack tip ... is imporant but the branching event seems stress intensity controlled and the high velocity a necessary but not a sufficient condition for branching". Similar observations traceable to an examination of the roughness of the fracture surfaces will be found in Kerkhoff's text (Kerkhoff, 1970).

The view that branching is a velocity or inertia controlled phenomenon has prevailed for a long time in spite of intermittent suggestions that it is associated with increased roughness of the fracture surface, (Clark and Irwin, 1966; Congleton and Petch, 1967) so that a link to micro fracturing at the crack tip has existed. However, the interpretation of branching has been heavily flavored in the past by the analytical perspective on this phenomenon. Continuum analyses have dealt of necessity with a rather idealized process/geometry because of the inherent mathematical difficulties even when "only" the linearized theory of elasticity is used.

Because of the mathematical idealization one should expect that only the gross features of the branching phenomenon will be captured. Thus one would hope to represent waves radiated from the branch point as well as the overall orientation of the branches after the event has occurred. Moreover it may be possible to assess the influence of waves impacting the crack tips *during* branching on this orientation. However, inasmuch as the physical process of branching is evolving to be rather complicated it is doubtful that such analyses can produce ***criteria for branching***. Inasmuch as the (linearized) analyses deal with a continuum - singular stress field and the branching phenomenon are associated with a fracture zone of finite dimensions - the two are basically incompatible.

True, just as the solutions of linear elasticity are occasionally used to estimate fracture initiation for plastically deforming solids so will singular solutions be used to estimate branching characteristics. For example, A. Kobayashi (1983) has provided such an estimate in which the distance r_o between a secondary flaw and the major crack tip on the one hand, and the stress parallel to the crack, on the other, play dominant roles. However, it appears that for Homalite 100 the length r_o is physically a bit too large and the criterion does not distinguish analytically between tensile and compressive stress in the crack-parallel dirction. Until either more experimental information or more advanced analyses become available such estimates will serve for engineering purposes.

Paths of the Branch Cracks

A persistently recurring question for analytical modelling purposes is whether branched cracks form smoothly from the main crack by turning through a deflection angle with high curvature or whether the branches emanate with a well defined angle from the main crack; in post mortem examination both seem to occur, but the possibility exists that observed definite angles have been formed as "flash backs" to the main crack. In Figs. 22 and 23 are shown real time photographs of a crack tip over a region of 3 mm in diameter in the process of branching in a 4.8 mm thick plate of Homalite 100 (Ravi-Chandar and Knauss, 1983b, 1984) which are only "marred" by the caustic effect that renders the individual extensions as broad shadow bands rather than sharply outlined entities. Because of the low contrast in the photographs line drawings of the branches have supplanted some of the actual photographs. Nevertheless it is clear that the branches begin as secondary cracks ***parallel*** to the main crack ***and turn continuously away from the latter***. One envisages thus the process of crack branching as a natural outgrowth of the micro fracturing at the crack tip according to the scheme depicted in Fig. 24.

Post mortem examination shows that the ***attempted*** or ***arrested*** branches do not span across the plate thickness; they may be at one of the plate surfaces or be ***totally contained in the interior of the plate***. Thus the truly three-dimensional character of the branch phenomenon alluded to at the end of the last section becomes apparent. It is well known that a crack will spawn branch attempts which may become arrested at various lengths. This phenomenon adds a statistical character to the branching process. However, the fact that (many) branches will propagate a considerable distance (cm's) before being arrested speaks for the argument that a criterion for successful branching (or a successful criterion for branching) must encompass not only the local crack tip conditions but the energetics of the surrounding field to allow branches to grow: The stresses in the immediate and intermediate vicinity of the crack tip must be large enough to a) cause branch inception and b) to sustain growth under the multiple unloading pulses from multiple, incipient branches ***to sustain some of them to grow***. A necessary condition for this to occur could be that branching can occur only "when the stress field increases," i.e. when $\partial\tau_{ij}/\partial t > 0$ in a sufficiently large domain.

Possible Importance of Stress Intensity Rate in Branching

Before concluding this section on crack branching it is appropriate to point out that most observations on branching have been made either as a result of explosive loading or in plates under steady far field loading; the former leads mostly to multiple branches while the latter produces bifurcation, which is the problem of greater ***analytical*** interest. Our present understanding of branching is based on the assumption that sufficiently high crack tip stresses will produce branching. Recall, however, that the formation and growth of the micro cracks is a competitive process whereby the microcracks must grow sufficiently rapidly by themselves to become independent of the main crack. In such a consideration it would seem important to include also in a branching criterion the rate with which crack tip stresses are established, i.e., the rate with which the stress intensity factor increases. Present day experiments are, generally speaking, not set up to consider this possible parameter.

CRACK ARREST

In practical importance the questions surrounding arrest of dynamically moving cracks are second only to those associated with initiation of growth. Because to

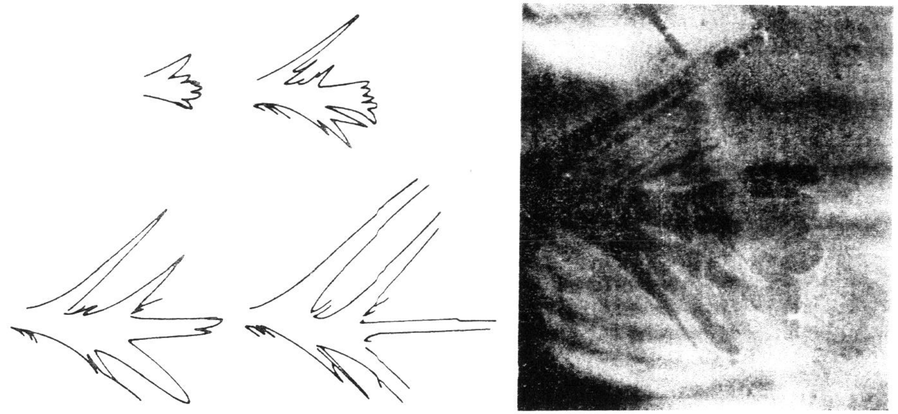


Fig. 22. High speed photomicrographs of the evolution of crack branching (Ravi-Chandar and Knauss, 1982c).

Fig. 23. Magnified photomicrograph showing continuous evolution of the crack branches (Ravi-Chandar and Knauss, 1982c).

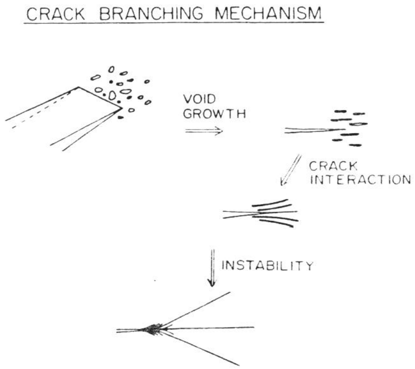


Fig. 24. Crack branching mechanism (Ravi-Chandar and Knauss, 1982c).

understand the conditions that lead to or aid crack arrest might prevent the growth of cracks to disastrous proportions such as in nuclear pressure vessels or in miles of gas pipe lines.

The first approach to crack arrest was to postulate that it was essentially a reverse process of crack initiation. If static conditions, in particular a static stress intensity factor, is responsible for crack initiation, then crack arrest should occur at a stress intensity which is calculated from the arrest geometry long after wave effects have died out. This was an attempt to circumvent the "troublesome" dynamic effects, but obviously neglected completely the considerably different deformation histories at the tip of cracks which start to propagate or come to rest. While this simple quasistatic argumentation is clearly open to question, it took considerable experimental and analytical effort to establish that a crack arrests when the stress intensity factor at the running crack tip drops to a particular value. This arrest value is less than the

value required for quasi-static initiation of dynamic crack growth in Homalite 100 (Bradley and A. Kobayashi, 1971) and in Araldite B and steel (Kalthoff, Beinert, and Winkler, 1977).

Much of the difficulties with understanding the conditions leading to crack arrest and the resulting confusion results from the use of specimens that mimic those in static fracture initiation tests. Because of their typically small dimensions it is extremely difficult to assess the dynamic stress field involving multiple wave reflections at the close boundaries, and in many cases the geometries do not allow a practical distinction between vibration and wave phenomena.

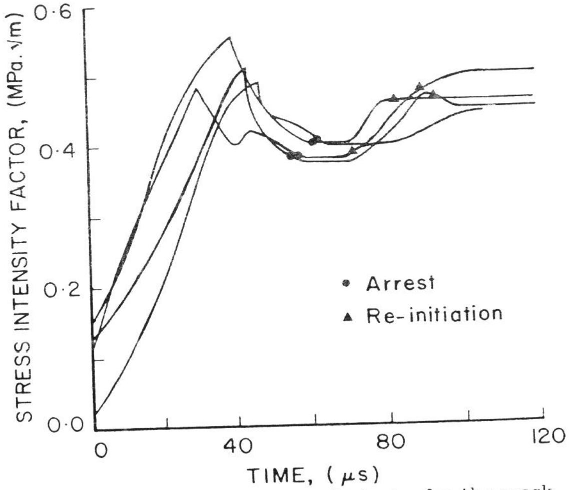


Fig. 25. Stress intensity factor histories for the crack arrest experiments (Ravi-Chandar and Knauss, 1982b).

In order to eliminate the possible effect of (multiple) interactions of the crack tip with reflected waves it is possible to arrange crack growth and arrest in large plates (of Homalite 100) and to follow the crack growth history with the method of caustics. Using a short trapezoidal pulse with the loading device illustrated in Fig. 2, one generates the stress intensity histories shown in Fig. 25 which produced the crack extension histories in Fig. 26. From the arrest times in Fig. 25, one determines the value of the stress intensity factor at which arrest occurred. This value, which is about 0.4 MPa$\sqrt{m}$ is 11% *less* than the stress intensity for initiation of crack growth. This result is in essential agreement with the work by Bradley and A.S. Kobayashi (1970) and by Kalthoff, Beinert, and Winkler (1977) in spite of the influence of wave reflections in the latter two investigations. One sees thus that there is a distinct, if not phenomenal difference, in the material response to initiation and arrest. From a practical point of

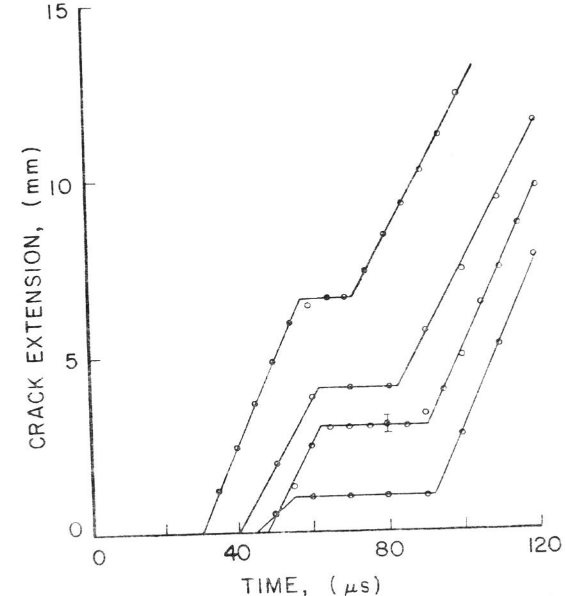


Fig. 26. Crack extension histories for the crack arrest experiments (Ravi-Chandar and Knauss, 1982b).

view this difference is such that use of quasi-statically determined fracture properties would lead to a non-conservative design, even if the proper dynamic analysis were performed for the instantaneous stress intensity factor.

Finally we address the question of the crack growth history as the crack approaches arrest. Both deceleration and abrupt arrest have been observed. While Bradley and Kobayashi (1970) as well as Kalthoff, Beinert and Winkler (1977) experience gradual deceleration Schardin (1959) as well as our own experiments on Homalite 100 show a sudden arrest from a constant velocity (see Fig. 26) without any marked or clear deceleration phase observable within the photographic time resolution of 5-10 μsec. This behavior appears somewhat similar to the situation in connection with initiation where both acceleration and abrupt crack growth are observed depending on the initial loading conditions.

DYNAMIC ANALOGUE TESTING

This final section is devoted to a *caveat in studying* dynamic fracture and in applying the results to engineering estimates. The concern arises from the observation that static fracture mechanics finds its usefulness in engineering designs because crack tip autonomy allows the transference of information gained from small specimens to large structures: one tests in the laboratory essentially an analogue specimen for the structure relying on stress analyses for the link between a full-scale structure and the laboratory test results. Matters become complicated when crack tip autonomy is violated in small laboratory specimens as, e.g., when "large scale" plasticity effects begin to dominate so that more careful and detailed analyses of the laboratory process becomes necessary before test measurements can be applied in large scale engineering designs.

In dynamic fracture it is common today to assume crack tip autonomy although reservations are being voiced (Kanninen, 1983). Since most work is being carried out on fairly high strength steels or other brittle (simulation) materials, large scale yielding effects are less likely to occur, especially since the high rates of crack tip loading would tend to significantly reduce that effect.

However, there is another aspect to crack tip autonomy in dynamic fracture that needs to be considered, namely the effect of rate of loading of the crack tip material. I refer here not to possibly intrinsic material rate dependence (viscoelastic or viscoplastic effects) but to the observation that under transient stress wave loading cracks seem to behave differently than under steady or slowly changing loads. We recall here that cracks tend to propagate at a velocity determined apparently by the initiation condition; that velocity changes only if a rapid stress pulse of sufficient magnitude impinges on the crack tip. Thus the rapidity with which the stresses at the crack tip (can) change has an influence on growth behavior.

Small specimens generate multiple wave reflection to the crack tip and these waves tend to be highly dispersive. Thus the crack tip experiences significantly different loading histories in a small laboratory specimen than in a large one, not to speak of a large structure. It is considerably more difficult to isolate transient phenomena in small laboratory specimens because the multiple wave reflections tend to smear out and thus mask phenomena within the normal time frame of our observations. What if our observations and deductions therefore do not allow us to fully characterize the dynamic fracture process as it would occur in a full scale engineering structure? It appears therefore that, perhaps, more careful attention to high temporal and spatial resolution should be paid in experiments and to more careful analytical examinations of laboratory experiments. Otherwise it might happen that we delude ourselves into believing that we "understand" dynamic fracture while in reality we only experience special phenomena inextricably tied to small laboratory specimens.

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