CRITERION FOR CRACK INSTABILITY UNDER SHORT PULSE LOADS

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ABSTRACT

The instability behavior of cracks loaded by a tensile pulse is not well predicted by expressions of static fracture mechanics when the pulse duration is comparable to the time required for a wave to run the length of the crack. Controlled experiments were performed on several polymers and structural alloys to obtain data that could help explain the response of a crack to a short load pulse and that could be used to establish a reliable criterion for dynamic crack instability.

The results showed the importance of dynamic effects and confirmed the main elements of a criterion that considers the dynamic stress intensity history experienced by the cracks.

KEYWORDS

Dynamic crack instability, stress wave loads, fracture criteria, stress intensity history, fracture mechanics.

INTRODUCTION AND BACKGROUND

The objective of this research was to establish a criterion for crack instability under a short pulse load by extending Griffith-Irwin fracture mechanics concepts to include time effects. Our approach was to generate a reliable data base for dynamic crack instability by performing experiments to ascertain the effects of well-defined stress pulses on well-characterized cracks, and to use the results to establish the relationship between crack size at instability and pulse duration and amplitude.

According to classical static fracture mechanics (Paris and Sih, 1964, for example) the stress σ necessary to cause crack instability varies inversely as the square root of the crack length a.[1] The usual instability criterion compares the crack tip stress intensity K with the fracture toughness K_c such that when

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[1] For simplicity of discussion we consider here only Mode I (opening mode) tensile loading of a sharp crack in a perfectly elastic material.

$$K = f\ (\sigma, a^{1/2}) \geq K_c \ ,$$

instability occurs. The fracture toughness K_c is a general measure of the resistance of a material to unstable crack growth. Under plane strain conditions $K_c (= K_{Ic})$ is geometry independent but may vary with strain rate and temperature.

When the load is applied very rapidly, the material may exhibit a different fracture resistance K_c, and if the load duration is short and comparable to the time required for a stress wave to run the length of the crack, the crack tip stress intensity may vary with time. This paper focuses on the time-dependence of the stress intensity and its effect on the instability condition. As for the material-related part, a constant dynamic fracture toughness value is assumed to exist and characterize the material for the strain rate considered.

When a stress wave strikes a crack, a complicated pattern of diffracted waves is generated and produces initial oscillations in the crack tip stress field. The time-dependent crack tip stress intensities produced by impringing step function loads have been computed by Sih, Embly, and Ravera (1968, 1969, 1971, 1972), and Achenbach (1970, 1972) and others. These results, depicted in Figure 1, show that the dynamic stress intensity K^{dyn} rises sharply with time ($K^{dyn} \propto t^{1/2}$), overshoots the equivalent static stress intensity K^{stat} by a considerable amount, and then reaches a constant static value after several damped oscillations. At early times K^{dyn} is independent of crack length, depending only on time and on the amplitude of the stress pulse. This is because the effective crack length that contributes to the crack tip stress intensity increases linearly with time as the stress wave propagates along its length and loads it. A single-valued parameter that characterizes this complicated stress field is needed to allow comparisons with the material property and to obtain an instability criterion.

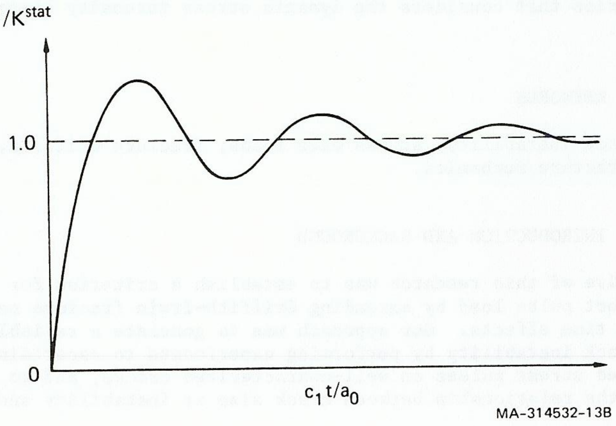

Fig. 1 Variation of K^{dyn}/K^{stat} with time for a crack loaded by a step wave (schematic)

Sih (1968, 1973) and Achenbach (1970, 1972) speculated that dynamically loaded cracks may become unstable at lower stress levels than cracks under equivalent static loads, because K^{dyn} briefly exceeds K^{stat}. These authors thus suggested that the maximum value of K^{dyn} determined crack instability.

An experiment reported by Shockey and Curran (1973), however, suggested that neither the static fracture mechanics nor the K^{dyn}_{max} criterion could explain dynamic crack instability. In this experiment a plate specimen of polycarbonate containing a distribution of internal penny-shaped cracks was impacted by a flying plate to produce a tensile pulse of known amplitude and duration. Cracks above a certain size propagated, whereas smaller cracks remained stable, and the dynamic fracture toughness was determined from the critical crack size, the amplitude of the tensile pulse, and the static fracture mechanics formula. However, when these results were used to calculate the crack instability behavior observed in a similar experiment with a lower amplitude pulse, a discrepancy was evident, demonstrating the inadequacy of both the static fracture mechanics criterion and the K^{dyn}_{max} criterion to describe crack instability under short pulse loads.

Kalthoff and Shockey (1977) explained these results by analyzing the early time stress intensity histories experienced by cracks of different lengths under stress pulses of different durations and proposed that for instability to occur, K^{dyn} must exceed K_{Id}, the dynamic toughness, for a certain minimum time. These authors postulate that static fracture mechanics can predict instability behavior when the ratio of pulse duration T_o to crack length a is such that $c_1 T_o/a > 20$, where c_1 is the longitudinal wave speed. Short cracks that can be traversed several times by a wave during the life of the stress pulse experience essentially constant stress intensity histories very similar to those produced by static loads, and hence their instability response is governed by the classical static fracture mechanics formulae.

Larger cracks experience more of the transient aspects of the stress intensity history so that the dynamic instability curve in stress-crack length space lies above the static curve, $\sigma \propto \sqrt{a}$. For cracks above a certain length, postulated to be $c_1 T_o/a < 1.6$, constant behavior is predicted, since all cracks greater than this size experience identical stress intensity histories.

These instability deductions are depicted graphically in Fig. 2 as a surface in stress amplitude/stress duration/crack length space. Unstable crack growth is expected for conditions of σ, T_o, and a that lie above the surface, whereas stable behavior is predicted for points below this surface. For short crack lengths and long stress durations, the instability surface is defined by the static criterion. However, for long crack lengths and short stress durations, time, and not crack length, is important. In this regime, the instability stress is a function only of the stress duration, so that all cracks longer than a certain length exhibit similar behavior. To check these hypotheses, stress wave loads were applied to cracks in an epoxy, in two steels, and in an aluminum alloy and their instability response was observed.

EXPERIMENTS AND RESULTS

Epoxy

A data base for dynamic crack instability was generated by casting arrays of appropriately sized internal penny-shaped cracks in epoxy and subjecting the cracks to rectangular, 2.04-μs-duration stress pulses (Shockey and Erlich). Six plate impact specimens of Epon Resin 815 epoxy[2] were cast from a single batch of epoxy in an effort to minimize specimen-to-specimen variation in mechanical properties. The specimens were 6.35 mm thick by 63.5 mm in diameter and each contained six judiciously spaced, 50-μm-thick, circular Mylar[3] disks having radii of 6.35, 3.18, 1.59

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[2] Epon Resin 815, Trademark, Shell Corporation, Houston, Texas.

[3] Trademark, E. I. DuPont de Nemours Co., Wilmington, Delaware 19898.

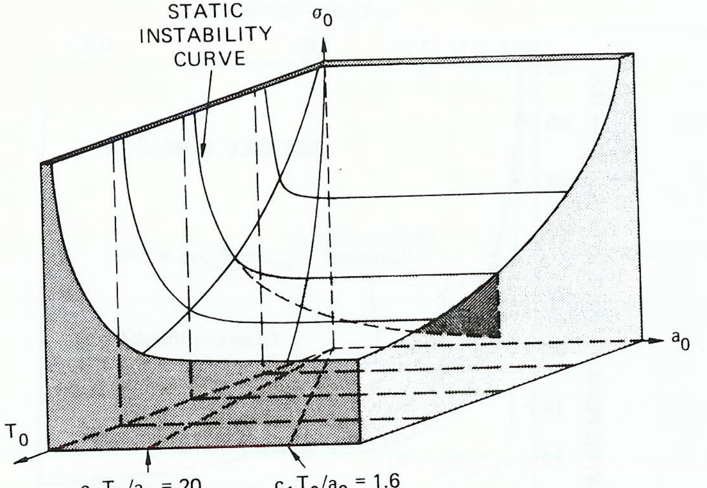

Fig. 2 Crack instability surface according to dynamic minimum-time stress intensity criterion

0.79, and 0.40 (two disks) mm. A light gas gun was used to accelerate a flyer plate against the specimen plates to achieve rectangular stress pulses of 2.04-μs duration. Impact velocities ranging from 0.0110 to 0.0275 mm/μs, corresponding to peak tensile stresses[4] ranging from 14.9 to 37.3 MPa, were chosen in an attempt to make different crack sizes grow in each specimen.

Figure 3 shows the results in stress-crack radius space at constant stress duration, T_o = 2.04 μs. The solid points, indicating crack instability, and the open circles, denoting no crack growth, define the regimes of crack instability and stability, respectively. The boundary between the two regimes represents the threshold conditions for crack instability and defines the curve required to evaluate proposed instability criteria. Some scatter exists in the data so that comparisons of proposed criteria must be made with a band rather than a sharp curve.[5] Nevertheless, the band provides a reliable indication of the shape and average location of the instability curve and thus allows discriminative evaluations of the proposed criteria.

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[4] A one-dimensional elastic wave propagation code, SWAP, computed the durations and amplitudes of the peak tensile stresses experienced by the individual specimens.

[5] Scatter is attributable in part to the relatively large inherent variability in mechanical properties, as has been found in static fracture toughness data, K_{Ic} = 1.1 ± 0.46 MPa $m^{1/2}$ (or $\sqrt{m}$).

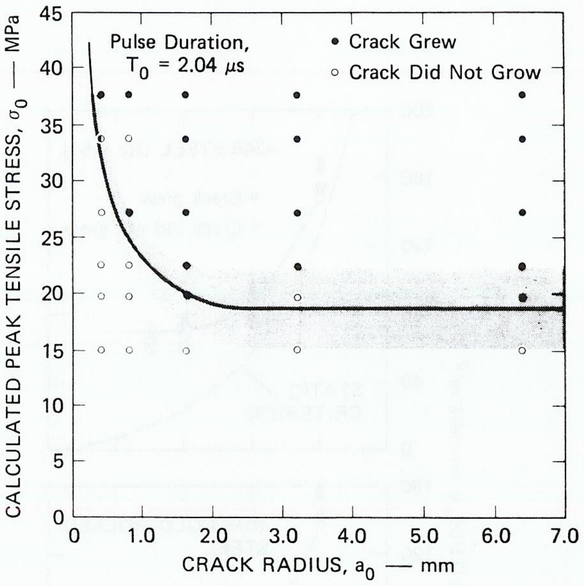

Fig. 3. Instability response of cracks subjected to 2.04-μs-duration stress pulses.

Structural Materials

Cracks in single-edge-notched strip specimens 1016 x 88.9 x 9.5 mm^3 of 4340 steel, 1018 steel, and 6061-T651 aluminum were subjected to 40-μs-long haversine-shaped tensile pulses of various amplitudes. Pulse loads were applied by pneumatically accelerating a cylindrical projectile along the specimen and against a massive block attached to one end of the specimen. This caused a tensile wave, whose profile was measured by a strain gage, to run back to the crack location. The amplitudes of successive pulses were increased in small steps until incremental crack growth could be detected by replicating the crack tip on the side of the specimen.

The results are shown in Fig. 4. For all three materials the stress for crack instability decreased strongly with crack length at short crack lengths, but tended to reach a constant value for crack lengths greater than about 60% of the specimen width. The instability curve predicted by the static criterion (dashed line) is shown for comparison and is discussed in the next section. Thus similar trends in the variation of critical stress with crack length were observed in epoxy, 4340 steel, 1018 steel, and aluminum.

EVALUATION OF INSTABILITY CRITERIA

Figure 5 compares the experimentally observed instability curve for epoxy with curves predicted by several proposed criteria. All criteria predict well the observed behavior at small crack lengths (a_o < 0.3 mm, c_1T_o/a_o > 20). In this region,

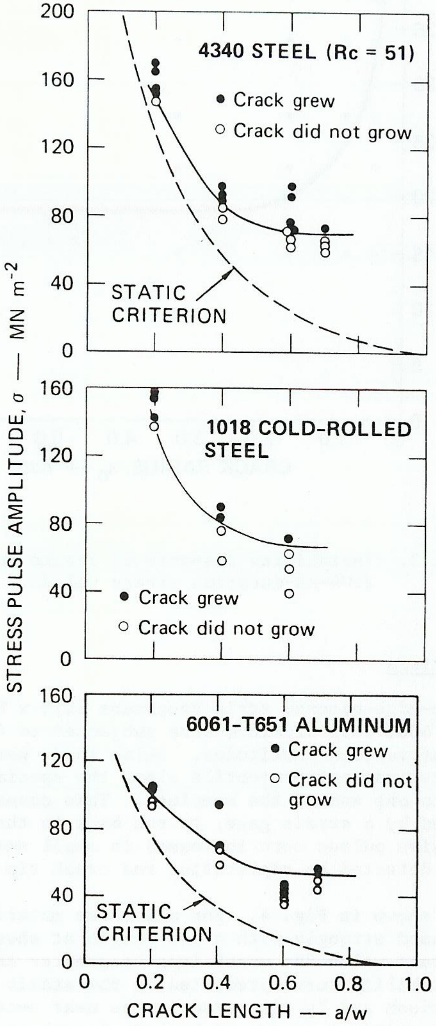

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Fig. 4 Observed instability behavior of cracks in three structural materials loaded by a 40-μs stress pulse and comparison with behavior predicted by static fracture mechanics

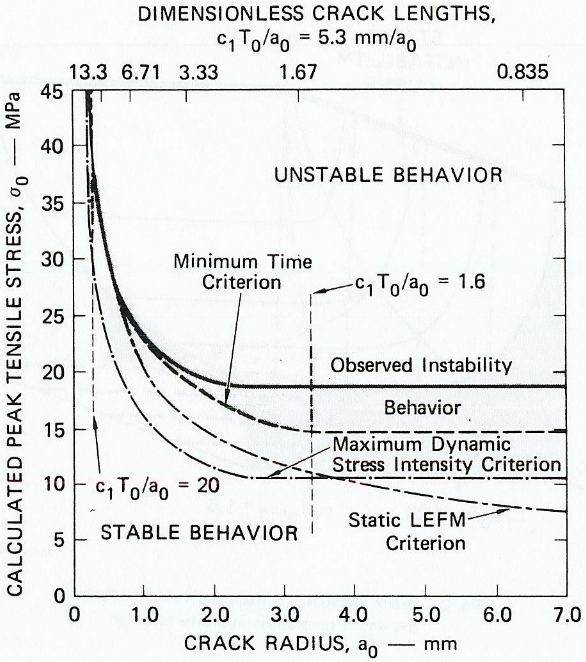

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Fig. 5. Comparison of experimentally determined dynamic crack instability curve with curves predicted by proposed instability criteria.

the stress wave has time to run the length of the crack several times before the pulse vanishes, so that the crack tip stress field approaches equilibrium and static conditions apply. For longer crack lengths where crack tip stress conditions are further from equilibrium, the predictions of all criteria are progressively worse. The continuous decrease in critical stress with increasing crack length predicted by static LEFM disagrees with the constant critical stress observed for cracks larger than about 2 mm. The maximum dynamic stress intensity criterion predicts constant behavior for cracks greater than 2.5 mm,[6] but the magnitude is significantly less than observed. Moreover, the magnitude of the critical stress predicted for shorter cracks is also less than observed.

The data are best described by the minimum time criterion, which accurately predicts the shape of the instability curve but slightly underpredicts the critical stress in the long crack length region. More consideration is needed to explain the observed discrepancy at long crack lengths.

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[6] For $c_1T_0/a_0 \geq 2.2$, the stress for instability stays constant although the crack length increases, because the stress pulse vanishes before the loading wave can run the length of the crack.

For the three structural materials, results similar to those in epoxy were obtained. Fig. 4 shows that the amplitudes of the critical pulses decreased with increasing crack length at a rate much less than predicted by the classical fracture mechanics formula. Furthermore, the maximum value of the dynamic stress intensity [as calculated by a dynamic finite element method (Homma and Shockey, 1980)] varied with crack length for the two steels, and thus K_{Imax}^{dyn} does not appear to be a useful dynamic crack instability criterion.

The structural alloy results are, however, in accord with the minimum time instability criterion. The instability curves at constant stress duration fall rapidly with crack length at short crack lengths, and then appear to approach a constant stress value at longer crack lengths (compare Figs. 2 and 4). Thus, the observed shape of the instability curve agrees with the predicted shape. A quantitative comparison must await additional experiments to obtain data for both shorter and longer pulse durations.

CONCLUSION

The crack instability criterion of classical static fracture mechanics can be modified to apply to high-rate, short-duration load situations. When the load is applied as a tensile pulse whose duration is comparable to the time required for a stress wave to run the length of the crack, unstable crack growth occurs if the crack tip stress intensity exceeds the fracture toughness for a certain minimum time. The predictions of this dynamic instability criterion are in qualitative accord with experimental results in polymers and metal alloys.

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