AFOSR-TR- 81-0402

LEVEL II

(8)

Report

AD A098791

F49620-77-C-0059

FRACTURE OF STRUCTURAL MATERIALS UNDER DYNAMIC LOADING

Donald A. Shockey
SRI International
333 Ravenswood Avenue
Menlo Park, California 94025

25 March 1981

Final Technical Report for Period 2 February 1977 - 1 February 1981

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
AFOSR/NE, Bldg. 410
Bolling Air Force Base
Washington, DC 20332

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81 5 12 059

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AFOSR-TR- 81 -0402
2. GOVT ACCESSION NO.: AD-A098 791
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): FRACTURE OF STRUCTURAL MATERIALS UNDER DYNAMIC LOADING
5. TYPE OF REPORT & PERIOD COVERED: Final technical rept. 2 Feb [redacted]77 [redacted] 1 Feb [redacted]81
6. PERFORMING ORG. REPORT NUMBER: PYU-6130
7. AUTHOR(s): Donald [redacted] A. Shockey
8. CONTRACT OR GRANT NUMBER(s): F49620-77-C-0059
9. PERFORMING ORGANIZATION NAME AND ADDRESS: SRI International, 333 Ravenswood Ave., Menlo Park, CA 94025
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: 61102F 2306/A1
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Office of Scientific Research, AFOSR/NE, Bldg. 410, Bolling Air Force Base, Washington, DC 20332
12. REPORT DATE: 25 Mar[redacted]81
13. NUMBER OF PAGES: 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Fracture; Tensile pulse; Dynamic crack instability; Heat of fracture; Method of caustics; Stress intensity history

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Classical concepts of Griffith-Irwin fracture mechanics were extended to include time effects and hence to apply to crack instability under dynamic loads. Theoretical considerations of the stress intensity histories experienced by cracks subjected to short pulse loads suggested that instability requires the crack tip stress intensity to exceed the dynamic toughness for a minimum time. This postulate was checked by experiments. Impact techniques were used to produce well-defined stress pulses in specimens of an epoxy, 4340 steel, 1018 steel, and 6061-T6 aluminum containing

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The relationship between dynamic initiation toughness and dynamic propagation toughness was addressed. The temperature histories in material near a rapidly propagating crack in a steel plate were measured and used to compute the heat of fracture and the dynamic propagation toughness. Simultaneous measurements of the dynamic stress intensity were made using the shadow optical method of caustics and high speed photography. The results indicate that more energy is delivered to the running crack tip than is absorbed there, suggesting that the conventional energy balance method for determining dynamic propagation toughness may lead to erroneous results.

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CONTENTS

ILLUSTRATIONS

I INTRODUCTION

Structures used by the United States Air Force must be designed to resist catastrophic fracture when subjected to dynamic loads. For example, aircraft components may experience short stress pulses from airborne debris, military projectiles, or intense bursts of laser or x-ray radiation. Landing gear and aircraft retaining cables on carrier ships experience dynamic loads at the end of each flight. To ensure safe design of such structures, a knowledge of the dynamic fracture behavior of the component materials is necessary.

This final technical report summarizes the results of a four-year research program aimed at improving our understanding of dynamic fracture behavior. The specific research objectives are given in the following section. Sections III and IV summarize our research on dynamic crack instability and rapid crack propagation. Section V lists the publications and presentations resulting from this work, and Section VI lists the project personnel and describes interactions with other scientists nationally and internationally.

II RESEARCH OBJECTIVES

This research program had two objectives. The first was to extend classical Griffith-Irwin fracture mechanics by accounting for time effects to obtain instability criteria for cracks under short pulse loads. The second objective was to perform critical experiments to measure the relation between energy delivered to and energy absorbed at the tip of a rapidly running crack. Specific research tasks were as follows:

(1) Produce arrays of well-defined internal macrocracks of given sizes, shapes, and spacing in a polymeric model material.

(2) Load the cracks with well-defined rectangular stress pulses and thereby generate a data base for dynamic crack instability.

(3) Use the data to evaluate a criterion for dynamic crack instability based on stress intensity considerations.

(4) Generate dynamic crack instability data in several structural alloys using single-edge-notched strip specimens and varying stress pulse duration, and compare results with the dynamic crack instability criterion.

(5) Recommend a simplified procedure for measuring dynamic fracture toughness that can become a standard, widely used, laboratory test.

(6) Begin to investigate the relationship between dynamic initiation toughness K_{Id} and dynamic propagation toughness K_{ID} by measuring the heat generated by a rapidly running crack.

In successfully completing all these tasks, we have made considerable progress in understanding the dynamic fracture behavior of materials. Major accomplishments include the following:

- Formulation of stress intensity history concepts that can explain the instability behavior of cracks loaded by short-lived stress pulses.

- Confirmation of the dynamic instability concepts (and proof of the inadequacy of static fracture mechanics concepts for short pulse load situations) by means of definitive experiments in a polymer and three structural alloys.
- Measurement of dynamic fracture properties and crack instability criteria for several materials.
- Simultaneous measurement of the energy delivered to and the energy absorbed by a rapidly propagating crack, showing the discrepancy between these energies and, thereby, indicating the magnitude of the error in assuming equality when calculating the dynamic fracture toughness of a running crack.
- Development of design concepts for modifying commercially available dynamic testing devices to allow routine measurements of dynamic fracture properties.

III DYNAMIC CRACK INSTABILITY

Background and Theoretical Considerations

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.* The usual instability criterion compares the crack tip stress intensity K with the fracture toughness K_c such that instability occurs when

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

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_d, 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 work focused 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 was assumed to exist and to 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 impinging step function loads have been computed by Sih, Embly, and Ravera (1968, 1969, 1971, 1972) and Achenbach (1970, 1972) and others. These results, shown in Figure 1, show that the dynamic stress intensity K^{dyn} rises sharply with time ($K^{dyn} \propto t^{1/2}$), overshoots the

*For simplicity of discussion, we consider here only Mode I (opening mode) uniform tensile loading of a sharp crack in a perfectly elastic material and neglect edge effects.

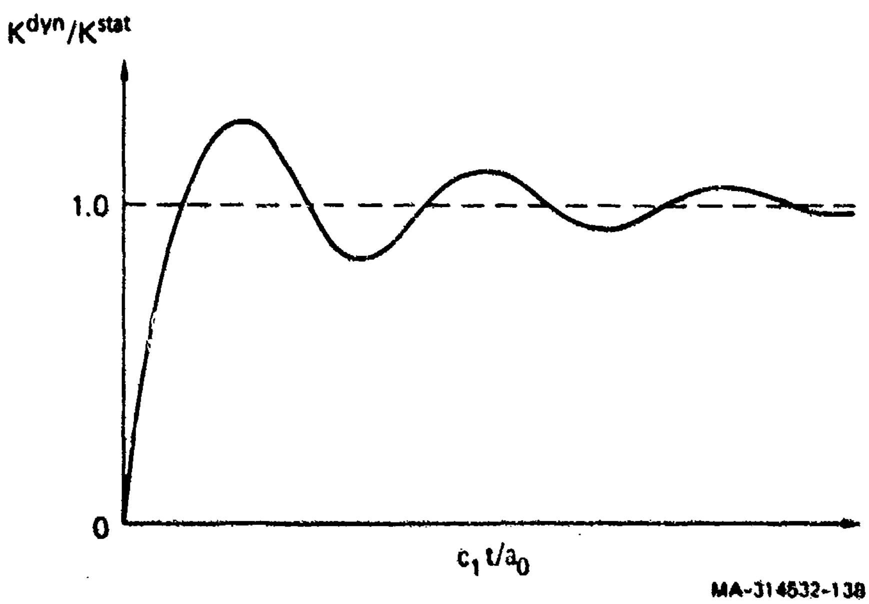

FIGURE 1 VARIATION OF K^{dyn}/K^{stat} WITH TIME FOR A CRACK LOADED BY A STEP WAVE (SCHEMATIC)

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.

Sih (1968, 1973) and Achenbach (1970, 1972) speculated that dynamically loaded cracks may become unstable at stress levels lower than those required for cracks under equivalent static loads because K^{dyn} briefly exceeds K^{stat}. These authors thus suggested that the maximum value of K^{dyn} determines 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 postulated that static fracture mechanics can predict instability behavior when the ratio of pulse duration T_0 to crack length a is such that $c_1T_0/a > 20$, 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; hence their instability response is governed by the classical static fracture mechanics formulas.

Because larger cracks experience more of the transient aspects of the stress intensity history, 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 $c_1T_0/a < 1.6$, constant behavior is predicted, since all cracks greater than this size experience identical stress intensity histories.

These instability deductions for penny-shaped cracks are diagrammed in Figure 2 as a surface in stress amplitude/stress duration/crack length space. Unstable crack growth is expected for conditions of σ, T_0, and a that lie above the 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 all cracks longer than a certain length exhibit similar behavior. To check these hypotheses, we applied stress wave loads to cracks in an epoxy, in two steels, and in an aluminum alloy and observed their instability response. The results are described in the following paragraphs.

Experiments and Results

Epoxy

A data base for dynamic crack instability was generated by casting arrays of appropriately sized Mylar* or Kapton* disks to serve as

*Trademarks, E. I. du Pont de Nemours & Co., Wilmington, Delaware 19898.

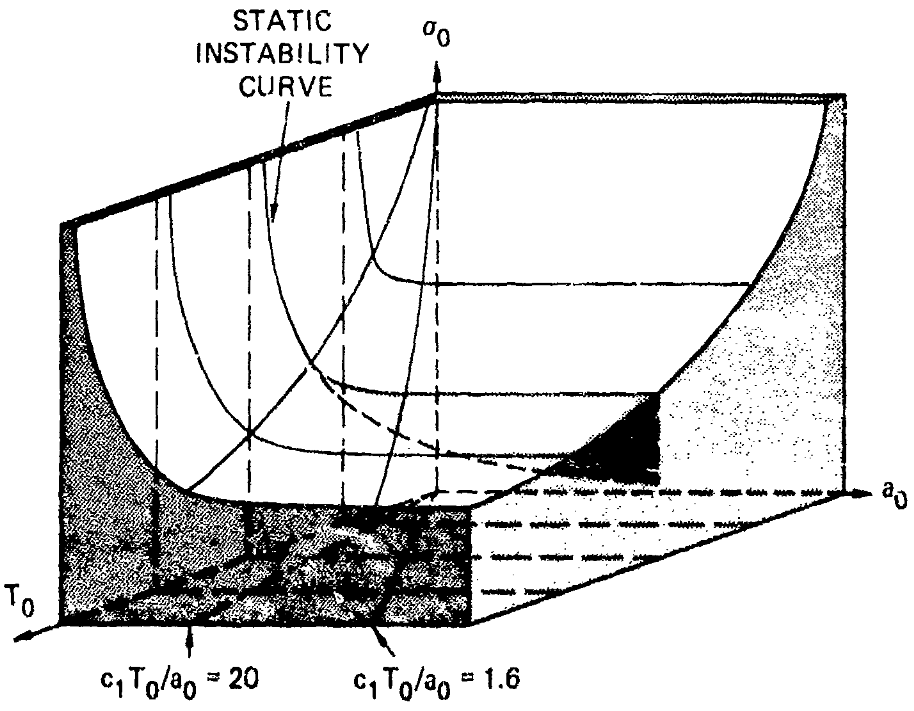

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FIGURE 2 CRACK INSTABILITY SURFACE ACCORDING TO DYNAMIC MINIMUM-TIME STRESS INTENSITY CRITERION internal penny-shaped cracks in epoxy (Figure 3a) and subjecting the specimens to rectangular, 2.04-μs-duration stress pulses (Shockey and Erlich, in preparation). Six plate impact specimens of Epon Resin 815 epoxy* 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 disks having radii of 6.35, 3.18, 1.59, 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** ranging from 14.9 to 37.3 MPa, were chosen in an attempt to make different crack sizes grow in each specimen. (Examples of the crack growth induced from Kapton disks are shown in Figure 3(b) and (c).)

Figure 4 presents the data in stress-crack radius space at constant stress duration T_o = 2.04 μs. The solid points, indicating crack growth, 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.

Because some scatter exists in the data, comparisons of proposed criteria must be made with a band rather than a sharp curve.+ 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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*Epon Resin 815, Trademark, Shell Corporation, Houston, Texas.

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

+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 $m^{1/2}$.

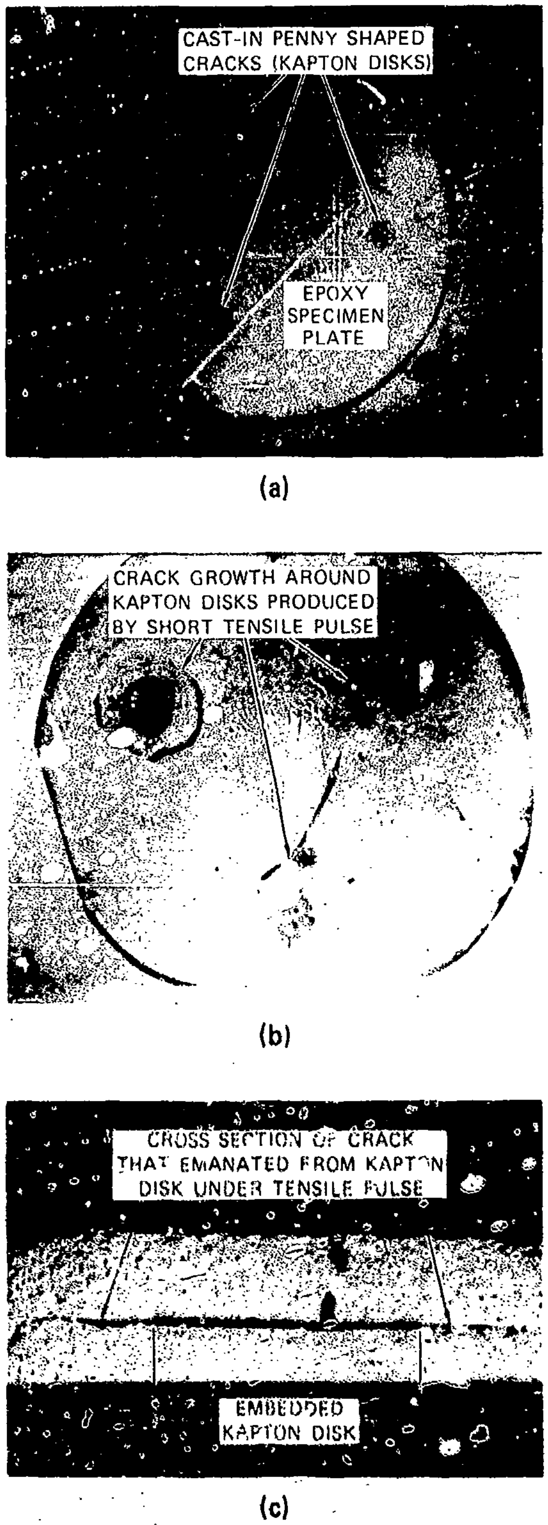

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FIGURE 3 CRACK GROWTH ABOUT EMBEDDED KAPTON DISKS RESULTING FROM APPLICATION OF A SHORT TENSILE PULSE

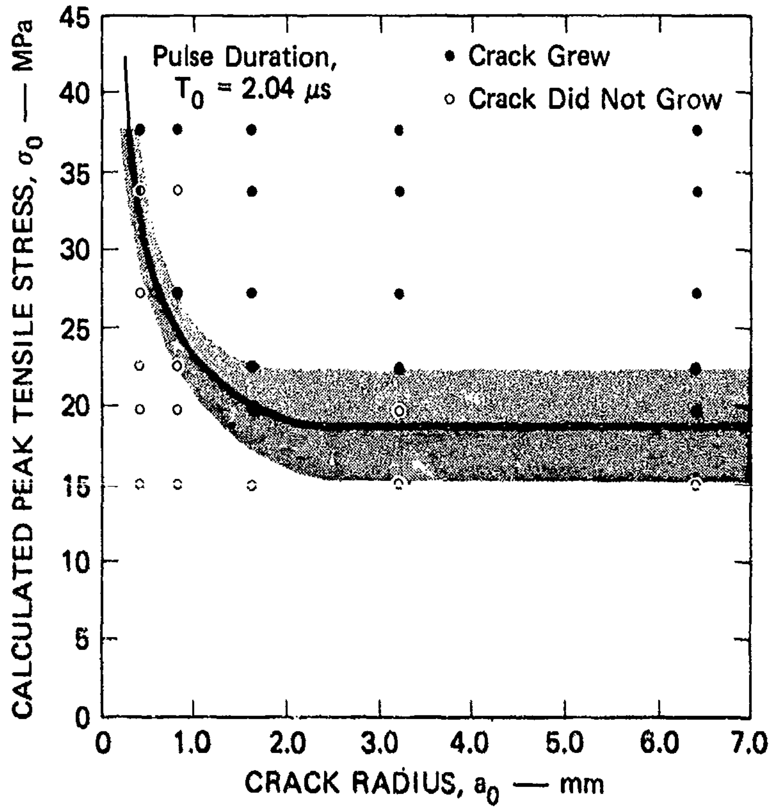

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FIGURE 4 INSTABILITY RESPONSE OF CRACKS IN EPOXY SUBJECTED TO 2.04-μs-DURATION STRESS PULSES

Structural Materials

Cracks in single-edge-notched strip specimens (1016 x 88.9 x 9.5 mm) 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 Figure 5. For all three materials, the stress necessary for crack instability decreased strongly with crack length (normalized by the specimen width w in Figure 5) 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 dicussed below. 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 6 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 ($a_0 > 0.3$ mm, $c_1T_0/a_0 > 20$). In this region, the stress wave has time to run the length of the crack several times before the pulse vanishes, so 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 fracture mechanics disagrees with the constant critical stress observed for cracks larger than about 2 mm. The maximum dynamic stress intensity criterion predicts constant behavior for

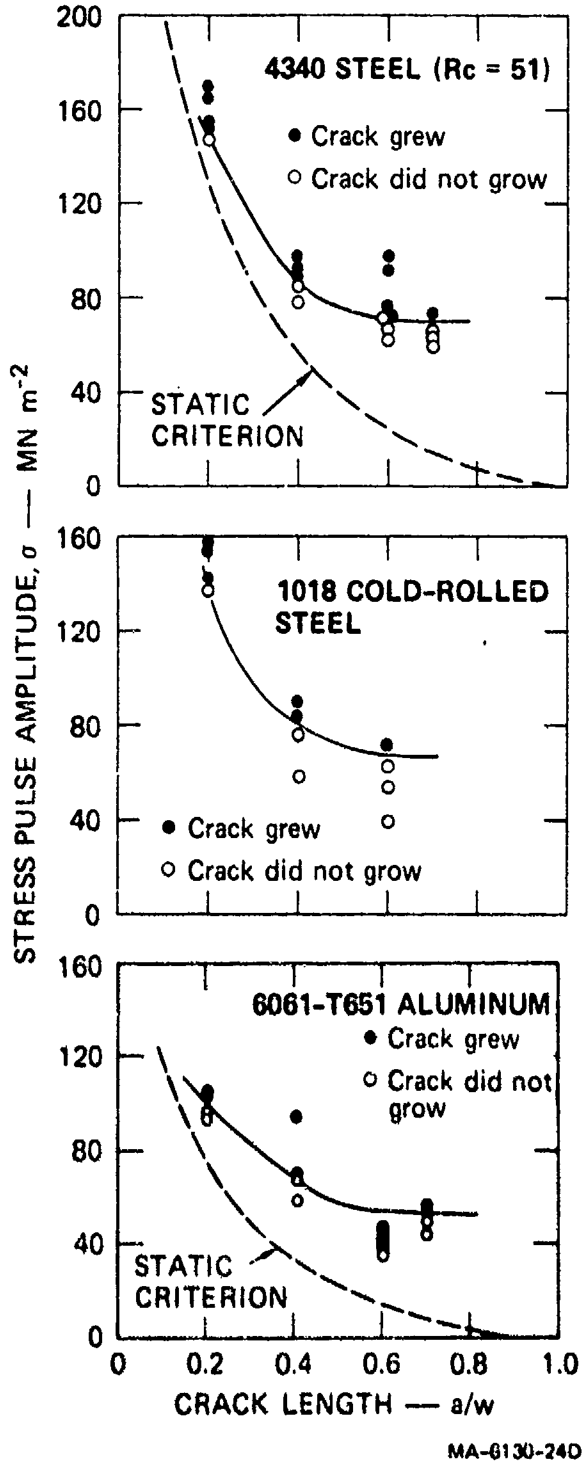

FIGURE 6 OBSERVED INSTABILITY BEHAVIOR OF CRACKS IN THREE STRUCTURAL MATERIALS LOADED BY A 40-μs STRESS PULSE AND COMPARISON WITH BEHAVIOR PREDICTED BY STATIC FRACTURE MECHANICS

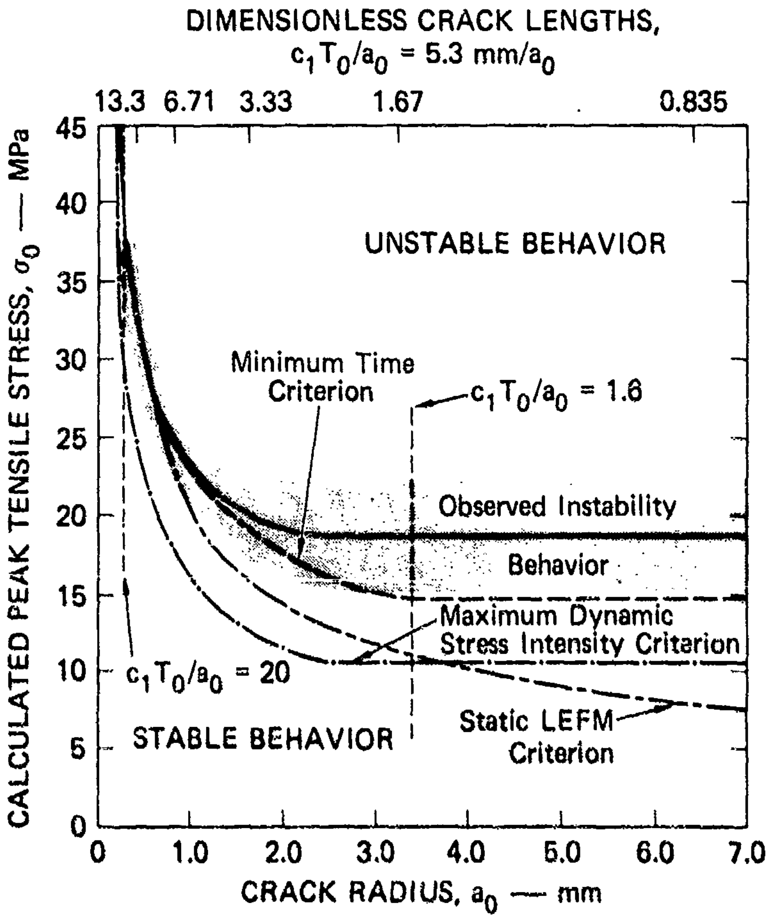

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FIGURE 6 COMPARISON OF EXPERIMENTALLY DETERMINED DYNAMIC CRACK INSTABILITY CURVE WITH CURVES PREDICTED BY PROPOSED INSTABILITY CRITERIA cracks greater than 2.5 mm,* but the magnitude is significantly less than observed. Moreover, the magnitude of the 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.

For the three structural materials, results similar to those in epoxy were obtained. Figure 5 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, in preparation) varied with crack length for the two steels, and thus K_{max}^{dyn} does not appear to be a useful dynamic crack instability criterion.

The structural alloy results are, however, in qualitative 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 Figures 3 and 5). Thus, the observed shape of the instability curve agrees with the predicted shape, and we can conclude that the crack instability criterion of classical static fracture mechanics can be modified to apply to high-rate, short-duration load situations.

Subsequent research efforts were directed at obtaining crack instability data at both shorter and longer pulse durations and, thereby, mapping the instability surface in crack-length, stress, pulse duration space. The dynamic instability behavior of cracks in 4340 steel strip

*For $c_1T_0/a_0 > 2.2$, 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.

specimens under 18-μs and 80-μs stress pulses was ascertained by the experimental procedure described earlier. The results, shown in Figure 7, support the minimum time criterion. The larger pulse durations allow longer cracks to follow the parabolic static instability curve, whereas the short 18-μs duration pulses produced the flat dynamic response curve for crack lengths as short as 0.2.

These results, taken together with the earlier results for 40-μs pulses (Figure 5a), can be used to construct the instability surface for 4340 steel, as shown in Figure 8. Comparison of this surface with the surface predicted from theoretical considerations of the stress intensity histories, Figure 2, shows the similarity and thus further verifies the theoretical concepts.

Routine Test Procedure

The understanding of dynamic crack instability gained from this research program can be used to design a testing apparatus and outline a testing procedure for routine evaluation of the dynamic fracture properties of materials. To be widely used, the testing procedure must be simple, and the test facility, specimens, and instrumentation must be inexpensive.

We suggest modifying a commercially available dynamic testing machine, such as a standard Charpy pendulum or dropweight tester, to produce and record tensile pulses having durations ranging from 10 to 90 μs and amplitudes up to 500 MPa. The durations require a series of striker plates of various dimensions; the stress amplitudes will require higher than normal striking velocities, which may be achieved with springs. The production of clean and isolated stress pulses requires simultaneous impact of the striker plates. When the striker plate is short, the shape of the pulse depends strongly on the lateral striker plate dimensions. The design of the striker assemblies, guided by intuition in our previous work, can be accomplished by two-dimensional finite difference wave propagation codes. The abilities of the strikers to produce the desired stress pulses can be tested by mounting the strikers on the impact machine and using strategically located strain gages to record the stress pulses resulting from the impact.

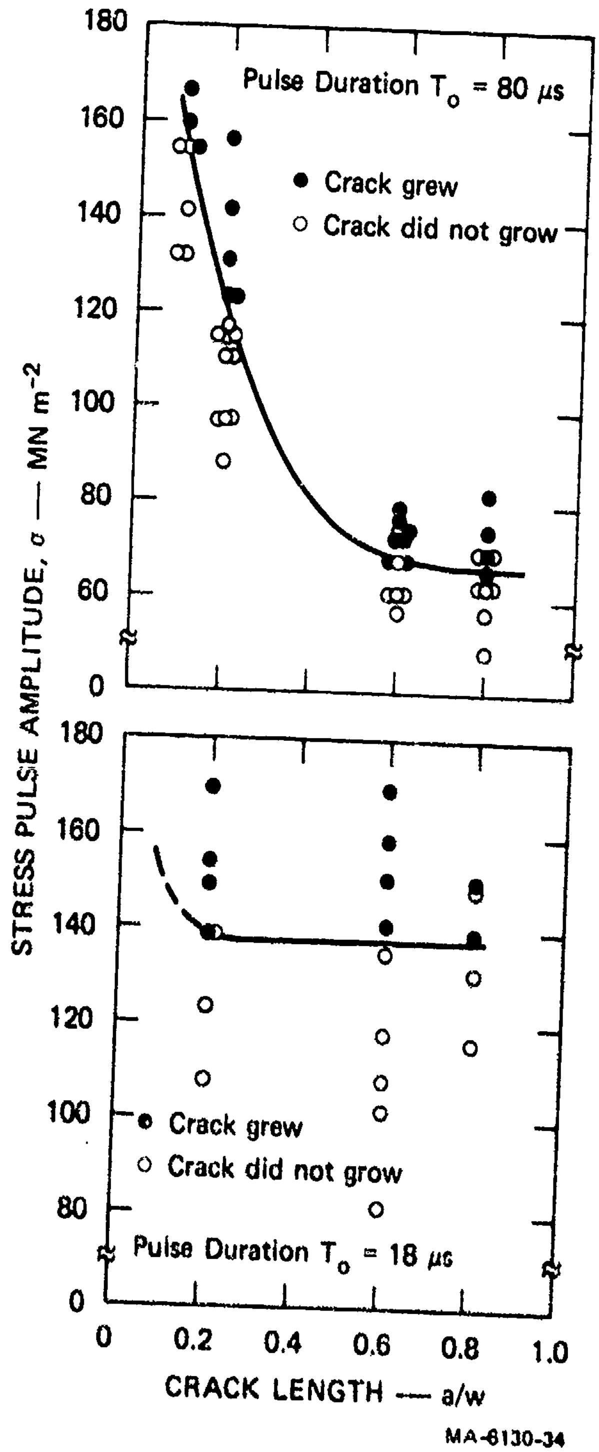

FIGURE 7 EFFECT OF PULSE DURATION ON INSTABILITY STRESS FOR CRACKS IN 4340 STEEL

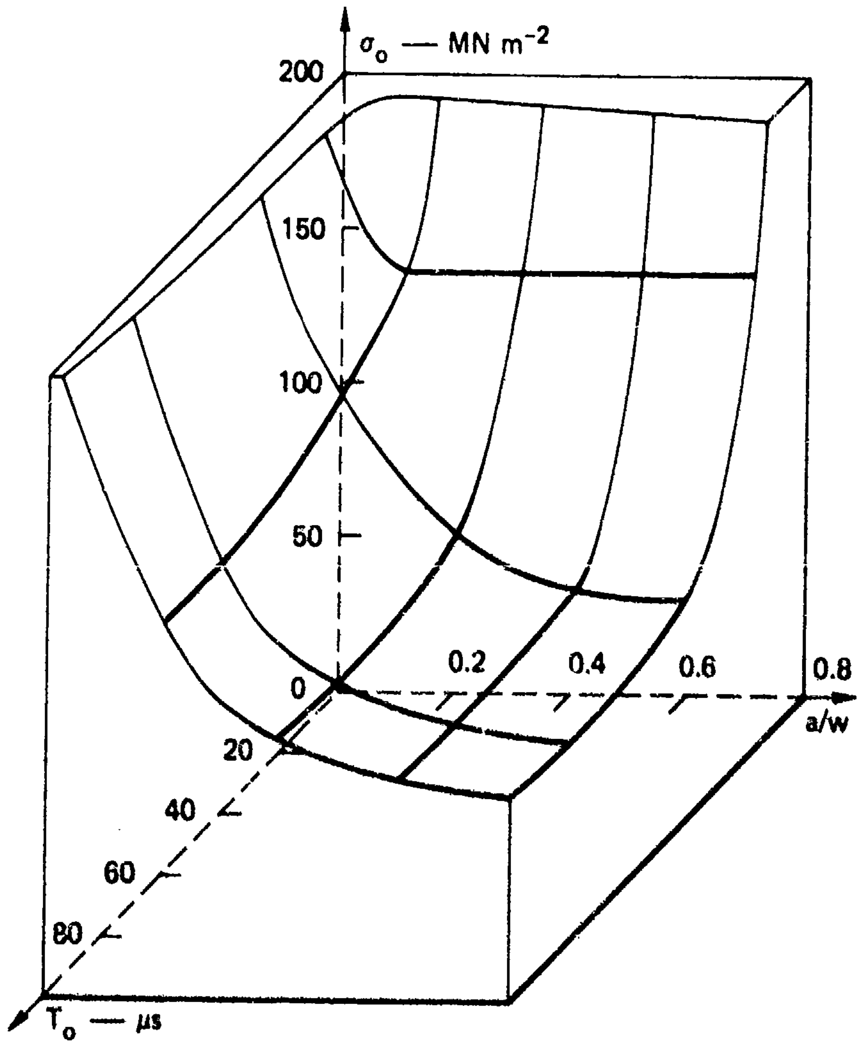

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FIGURE 8 INSTABILITY SURFACE FOR CRACKS IN 4340 STEEL STRUCK BY SHORT-LIVED STRESS PULSES

Amplitudes of subsequent tensile stress pulses must be less than the initial one. In the present work, adequate damping of subsequent tensile pulses was achieved by gradually decelerating striker plates and projectiles with energy-absorbing aluminum honeycomb, but other reusable and tunable energy-absorbing systems could be incorporated.

Finally, instrumentation, if needed, may be attached to the striker of the machine to avoid having to instrument each specimen, and the striker should be fixed and impacted by the specimen. These ideas will be pursued in a follow-on contract with AFOSR.

IV DYNAMIC CRACK PROPAGATION

Dynamic fracture toughness can mean either the resistance exhibited by the material to propagation of an existing crack subjected to a dynamic load (i.e., a stress pulse) or the resistance exhibited by the material to a rapidly running crack under, say, a static load. In the research described in the preceding section, the former case, dynamic crack initiation, was investigated. In this section we discuss our investigation of the latter situation, deducing the dynamic fracture toughness associated with a rapidly running crack, K_{ID}, from measurements of temperature histories near the crack path. The results were compared with the energy delivered to the crack tip as measured simultaneously by the method of caustics.

Background

The energy absorbed by a propagating crack is absorbed by plastic flow and fracture within a relatively small (compared with specimen dimensions) volume of material in the vicinity of the crack tip. Calculations show that, in metals, the energy absorbed in creation of new surface area is negligible compared with the plastic energy; therefore, the fracture toughness associated with a running crack is determined by the plastic energy expended at the crack tip.

The plastic energy is dissipated as heat, which flows away from the crack plane into both halves of the specimen, causing small, transient temperature elevations. If the temperature history of material near a running crack can be measured, the heat energy and hence the fracture toughness of the running crack can be calculated by solving the appropriate heat flow equation. Thus the results will yield direct measurements of dynamic propagation toughness K_{ID}, which can be compared with the dynamic initiation toughness K_{ID} measured in the impact experiments in this program.

A thermocouple technique was used to measure temperatures associated with rapidly propagating cracks and to obtain fracture energies from the temperature histories. A NATO travel grant was awarded to Dr. D. A. Shockey, allowing him to make these measurements at the Institut für Werkstoffmechanik in Freiburg, Germany, where he was able to make simultaneous measurements of the dynamic stress intensity at the rapidly moving crack tip using unique German equipment to apply the method of caustics. Expert technical assistance was provided by J. F. Kalthoff, W. Klemm, S. Winkler, and A. Wolf. This effort, which was highly successful, has been written up in preparation for submission to a technical journal and is described briefly here.

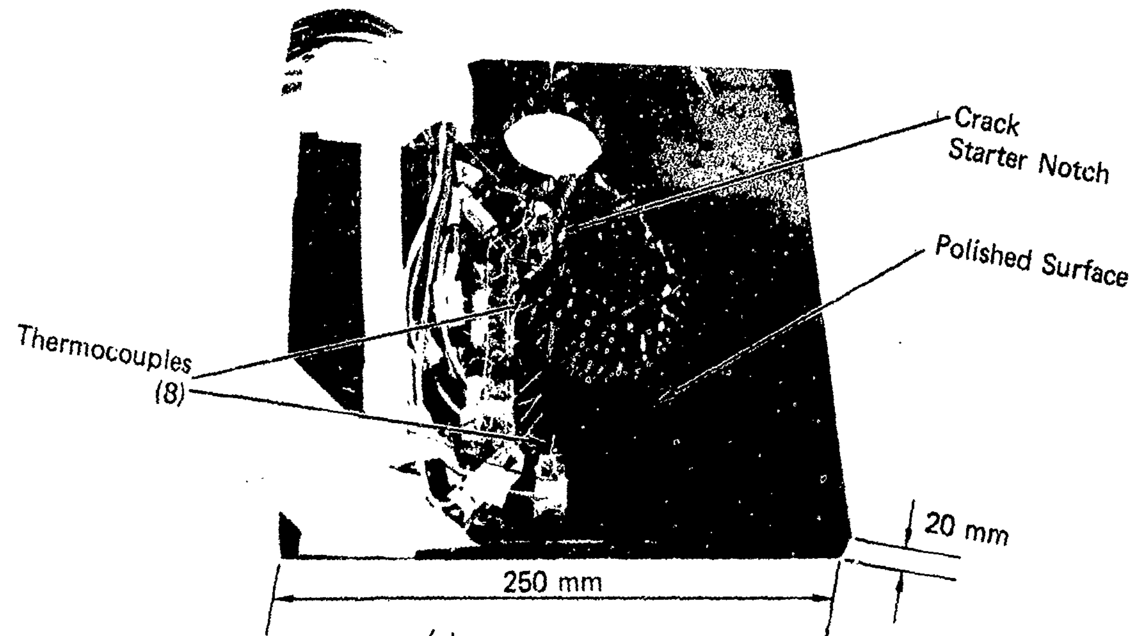
Specimens

Six compact fracture specimens 250 by 250 by 20 mm were machined from a high-strength maraging steel* and then hardened to R_c 56 (yield strength = 2100 MN m^{-2}) by heating to 480°C for 4 hours. The static fracture toughness K_{Ic} was measured to be 50 MN $m^{-3/2}$. A 208-mm-long slot having a 45° chevron tip served as the starter notch. One side of each specimen was lapped and polished to a mirror finish in preparation for measuring K_I^{dyn} by the caustics method. Four to ten 30-μm-diameter constantan wires were spot-welded to the specimen near the expected crack path to monitor temperature histories and allow subsequent calculations of K_{ID}. Figure 9 shows a prepared specimen before and after it was placed in the testing machine. The specimens were loaded in a hydraulically activated mechanical testing machine by the transverse split wedge technique. A range of crack velocities was achieved by causing crack initiation to occur under different specified stress intensities K_{IQ}.

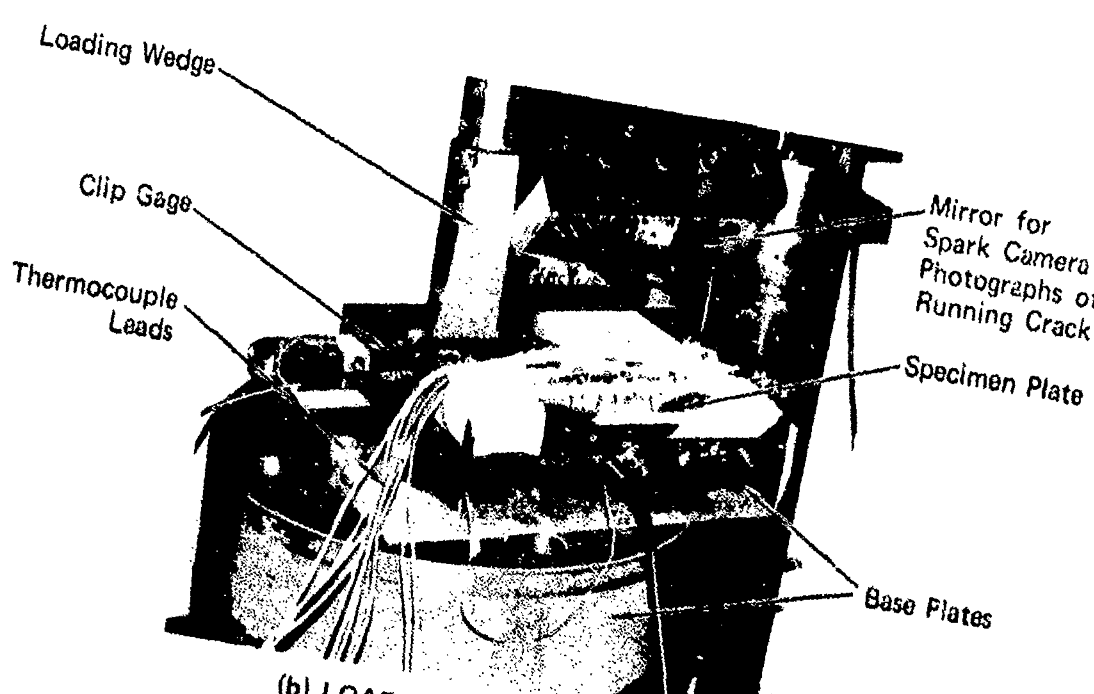
Dynamic Stress Intensity Measurement

The energy delivered to the crack tip was measured by the shadow optical method of caustics (Kalthoff et al., 1977). In this method, light incident on the specimen surface is reflected into a camera. A dark shadow spot appears at the crack tip because the surface there is

*The German designation for the steel is HFX 760. It has a nominal composition of 18% Ni, 9% Co, 4.8% Mo, 0.9% Ti, and <0.03% C and corresponds to the American 18 Ni maraging grade 300.



(a) SPECIMEN



(b) LOADING ARRANGEMENT

FIGURE 9 SPECIMEN AND LOADING ARRANGEMENT FOR MEASURING ENERGY DELIVERED TO AND ABSORBED AT TIPS OF PROPAGATING CRACKS

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deformed inward by the high stresses that exist at the crack tip. The size of the shadow spot is a measure of the crack tip stress intensity K_I^{dyn} and hence a measure of the energy available at the crack tip:

$$K_I^{dyn} = M\ F(v)\ D^{5/2} \qquad (1)$$

where M is a constant that depends on material properties and the experimental arrangement, F(v) is a dimensionless factor that corrects for the effect of crack speed, and D is the diameter of the shadow spot normal to the fracture plane.

The energy delivered to the crack tip as the crack propagated was determined at 24 locations by photographing the shadow spot at the running crack tip every few microseconds with a spark camera.

Heat of Fracture Measurement

The energy absorbed at the tip of a running crack was determined from the temperature histories of material near the crack plane as measured by sensitive thermocouples. Four to ten constantan wires 30 μm in diameter were spot-welded to the specimen surfaces at locations along the expected crack path and slightly (0.7 to 2.0 mm) to the side of the expected crack path. An equal number of constantan wires were spot-welded to a plate of the same steel to serve as reference thermocouples.

The time-temperature-distance data were used to solve the heat-flow equation and to calculate the heat liberated by the crack at various locations along its path. The liberated heat represents nearly all the energy absorbed by the crack and is thus a measure of the dynamic fracture toughness K_{ID}.

To obtain approximate values of the heat generated by the propagating crack Q and the dynamic fracture toughness K_{ID}, we used the measured maximum temperature values T_{max} to solve the one-dimensional heat flow equation:

$$Q = \Delta T_{max}\ y\ \sqrt{2\pi e}\ \rho c = (1 - \nu^2)\ \frac{K_{ID}^2}{E} \qquad (2)$$

where y is the distance between the fracture surface and the thermocouple, e is the constant 2.718, and the other symbols are properties of HFX 760 steel given below:

Density, ρ	8040 kg m^{-3}
Specific heat, c	477 J $kg^{-1}{}^{\circ}C^{-1}$
Poisson ratio, υ	0.32
Elastic modulus, E	183 x 10^{11} N m^{-2}

Results and Discussion

Seven experiments were performed at crack velocities ranging from 500 to 1200 m s^{-1}. A typical series of shadow optical photographs of a propagating crack tip is shown in Figure 10. The diameter of the shadow spot in each frame is carefully measured, and the dynamic stress intensity K_I^{dyn} at the crack tip at that instant of time was calculated from equation (1).

A record of the temperature history obtained by a thermocouple is given in Figure 11. No change in temperature is detected initially after triggering because the heat generated by the crack requires time to flow to the thermocouple location. When the heat wave arrives, the temperature rises sharply to a maximum (typically several tenths of a centigrade degree) and then falls off slowly as the heat pulse continues to dissipate in the specimen.

The first five experiments produced non-steady crack velocities and substantial scatter in the K_{ID} and K_I^{dyn} data. We suspected that residual stresses were responsible,* so the final two experiments (17 and 18) were performed on specimen plates that were given a stress relief anneal. Spark camera photographs of the propagating crack in the stress-relieved specimens showed two steady-state crack velocities, with the initial velocity being slightly greater than the second, as is typical of compact specimens. Furthermore, the scatter in K_I^{dyn} values was markedly reduced. These results show the important influence of residual stresses on dynamic toughness evaluation.

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*The heat treatment and subsequent quench given to the specimens to obtain the desired mechanical properties caused the plates to warp slightly, which suggested the existence of residual stresses.

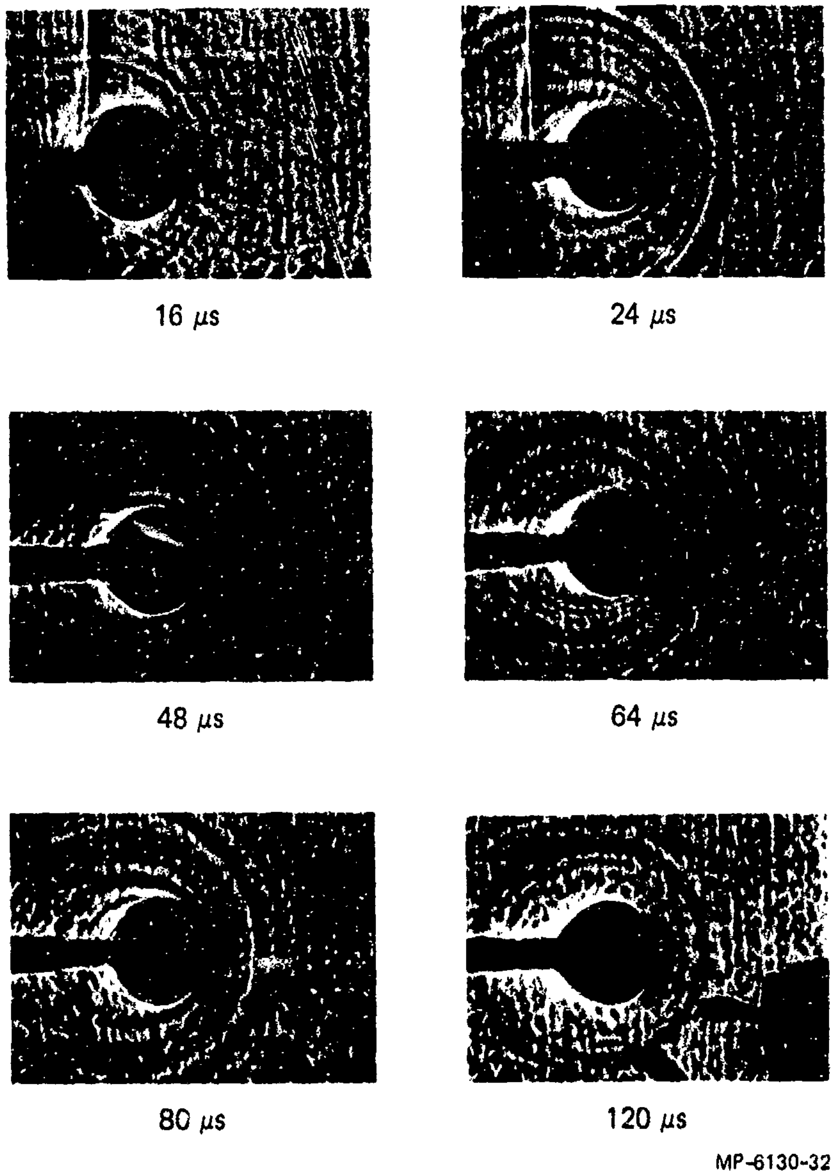

FIGURE 10 SHADOW SPOTS AND CAUSTICS AT THE TIP OF A RAPIDLY RUNNING CRACK IN HFX 760 STEEL

Note stress waves emanating from the moving tip.
(Only 6 of the 24 spark camera photos are shown.)

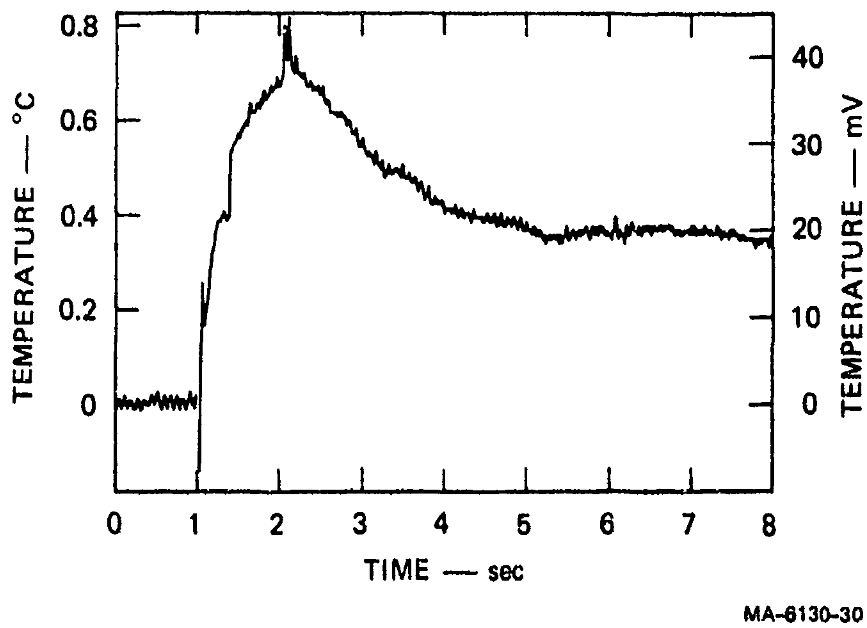

FIGURE 11 MEASURED TEMPERATURE HISTORY EXPERIENCED BY MATERIAL NEAR THE PATH OF A RAPIDLY PROPAGATING CRACK

Figure 12 shows the variation of K_I^{dyn} and K_{ID} with crack length for the two stress-relieved specimens. The K_{ID} values are significantly smaller (10% to 50%) than the K_I^{dyn} values, indicating that considerably more energy is delivered to the crack tip than is absorbed there. However, these results must be regarded as preliminary because of uncertainties in the residual stress state of the specimens and because an approximate heat-flow analysis was used.* Additional work is necessary to more accurately assess the relationship between the energy delivered to and the energy absorbed by rapidly propagating cracks.

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* The temperature histories calculated assuming one-dimensional heat flow did not replicate the measured histories, and so the K_{ID} values obtained from equation (2) are in some error. A three-dimensional analysis of heat flow in the specimen geometry is needed to obtain more accurate values of K_{ID}.

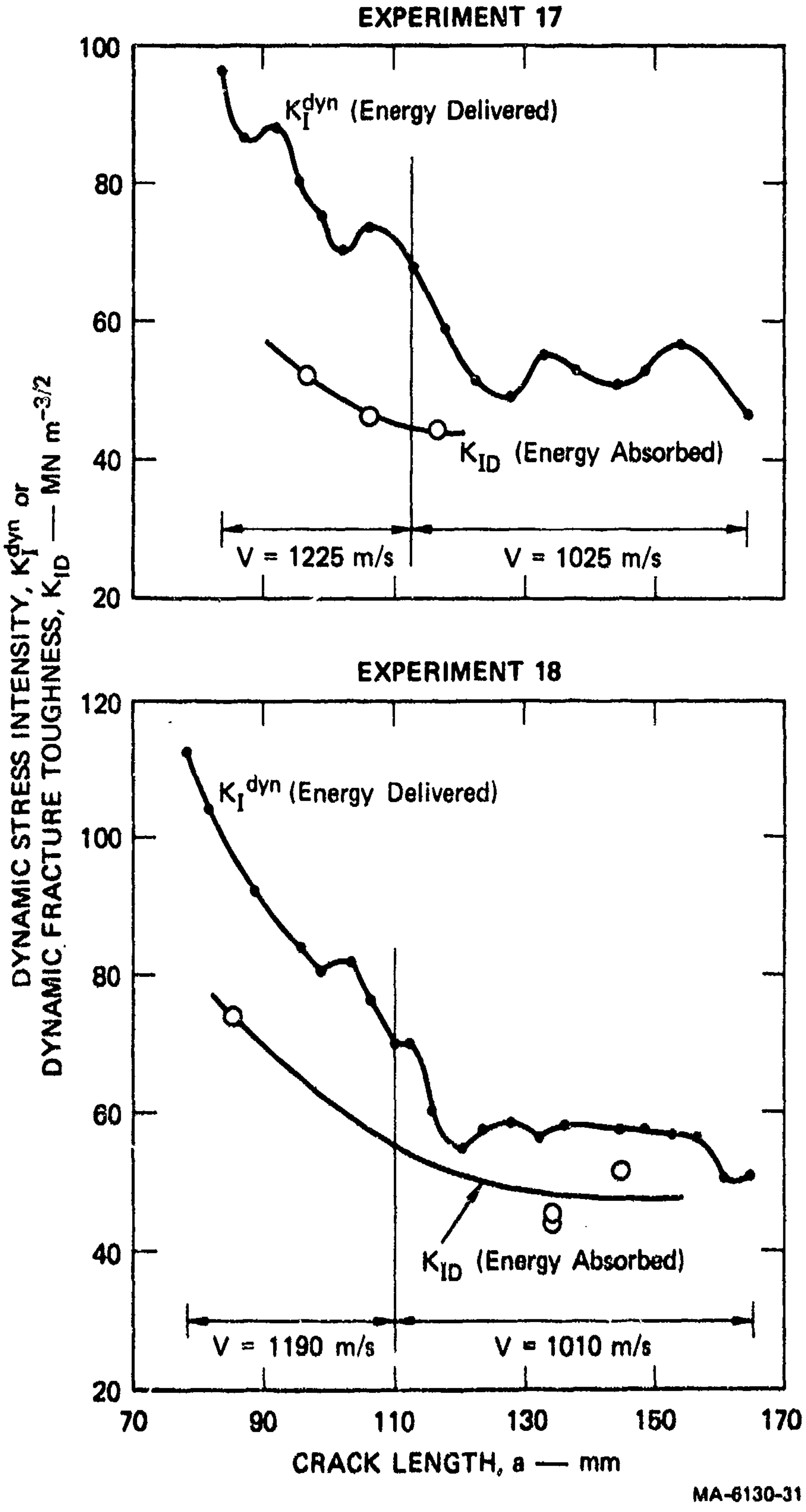

FIGURE 12 COMPARISON OF ENERGY DELIVERED TO AND ENERGY ABSORBED BY A RAPIDLY PROPAGATING CRACK

V PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made under the current contract are listed below.

Publications

J. F. Kalthoff and D. A. Shockey, "Instability of Cracks Under Impulse Loads," J. Appl. Phys. 48, (3), 984-993 (March 1977).

D. A. Shockey, J. F. Kalthoff, H. Homma, and D. C. Erlich, "Criterion for Crack Instability Under Short Pulse Loads," Advances in Fracture Research, D. Francois et al., Eds. (Oxford and Pergamon Press, New York) pp. 415-423.

H. Homma and D. A. Shockey, "Response of Cracks in Structural Materials to Short Pulse Loads--Experimental Results," to be submitted to the Journal of the Mechanics and Physics of Solids.

H. Homma and D. A. Shockey, "Response of Cracks in Structural Materials to Short Pulse Loads--Calculations and Analyses," to be submitted to the Journal of the Mechanics and Physics of Solids.

D. A. Shockey, and D. C. Erlich, "Instability Behavior of Cracks Under Short-Duration Loads," to be submitted to the International Journal of Fracture Mechanics.

D. A. Shockey, J. F. Kalthoff, W. Klemm, and S. Winkler, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," to be submitted to Experimental Mechanics.

Presentations

D. C. Erlich and D. A. Shockey, "Instability Conditions for Cracks Under Short-Duration Pulse Loads," Topical Conference of Shock Waves in Condensed Matter, meeting of the American Physical Society, Washington State University, Pullman, Washington, June 11-13, 1979.

D. A. Shockey, "Instability Conditions for Cracks Loaded by Short Stress Pulses," Poulter Seminar, SRI International, Menlo Park, CA, December 12, 1979.

D. A. Shockey, "Dynamic Crack Instability," Institut CERAC, Ecublens, Switzerland, May 19, 1980.

D. A. Shockey, "Dynamic Crack Instability," Institut für Werkstoff-mechanik, Freiburg, Germany, May 21, 1980.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," Poulter Laboratory Seminar, SRI International, Menlo Park, CA, June 1980.

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Symposium on Crack Formation and Propagation, sponsored by Polish Academy of Science, International Union of Theoretical and Applied Mechanics and the International Center for Mechanical Sciences, Tuczno, Poland, March 23-27, 1981.

D. A. Shockey, "Criterion for Crack Instability Under Short Pulse Loads," Fifth International Conference on Fracture (ICF5) Cannes, France, March 29-April 3, 1981.

VI PERSONNEL AND ACTIVITIES

The following professional personnel were associated with this research effort.

D. A. Shockey, principal investigator
D. C. Erlich
H. Homma
J. F. Kalthoff
W. Klemm
S. Winkler

Five publications in scientific journals will result from this program. Air Force personnel have been kept abreast of technical developments through the annual reports, and contact was maintained throughout the program with Dr. A. H. Rosenstein of the Air Force Office of Scientific Research. Dr. Theodore Nicholas, Metals Behavior Branch of the Air Force Materials Laboratory at Wright-Patterson Air Force Base, was periodically consulted by telephone, and he visited Dr. Shockey at SRI International in November 1980 to obtain a complete, first-hand account of the accomplishments in the program.

This program has attracted international attention. The principal investigator, D. A. Shockey has been invited to a special dynamic fracture conference in Poland in 1981 to present and discuss the results. A paper describing the results of the dynamic crack instability experiments has been accepted for presentation and publication at the Fifth International Conference on Fracture to be held March 1981 in Cannes, France.

Furthermore, the North Atlantic Treaty Organization granted travel funds and living expenses to the principal investigator to allow him to use a unique optical arrangement in Germany in his dynamic fracture experiments. These experiments were highly successful and are reported in Section IV of this report. A paper describing this work and the results has been prepared and will be submitted for publication in a technical journal.

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