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DYNAMIC FRACTURE BEHAVIOR OF STRUCTURAL MATERIALS

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A high-spatial-resolution temperature measuring instrument, based on laser thermoprobe concepts, was constructed and evaluated for use in K_{ID} determinations for fast running cracks. By monitoring the change in intensity of a monochromatic light beam passing through a thin CdS film, we could measure the temperature of the film substrate to 0.25°C over a range of 150°C. Thus the technique appears suitable for dynamic fracture investigations. Compact fracture specimens and transverse-wedge loading fixtures have been machined in preparation for K_{ID} determinations in the second research year. Development of the thermoprobe will continue with the goal of improving the temperature sensitivity.

I SUMMARY

The goals of this research program are to first develop and apply procedures for obtaining more accurate measures of dynamic fracture initiation and propagation toughnesses, and then to establish the relationship between them. The dynamic initiation toughness, K_{Id}, will be obtained by applying short pulse loads to SEN specimens and using minimum time crack instability criteria. The dynamic propagation toughness, K_{ID}, will be obtained by measuring the temperature histories in material near the tip of a fast running crack.

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II 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.

A related dynamic fracture problem concerns rapidly running cracks. For example, it is often desirable to know whether a crack, once initiated, will arrest before it reaches a component boundary and thereby preserve the integrity of the structure. Thus, to ensure safe design of Air Force structures, a knowledge of the dynamic fracture behavior of the component materials is necessary. The research being conducted in this program is aimed at improving our understanding of dynamic fracture. This annual report reviews the specific program objectives and summarizes the progress during the first research year.

III STATUS OF RESEARCH EFFORT

Objectives

To obtain more accurate measures of dynamic fracture initiation and propagation toughnesses and to establish the relationship between them, we proposed to accomplish the following research tasks in a four year program:

Task 1 - Design and construct an improved impact testing device based on the new understanding of the role of load duration in crack instability behavior.

Task 2 - Use this device to generate the necessary data to develop a reliable theory for dynamic crack instability.

Task 3 - Measure critical conditions and establish criteria for crack instability under mixed-mode, short-pulse loads.

Task 4 - Establish the relationship between the dynamic fracture toughnesses associated with stress-wave-triggered initiation K_{Id} and rapid crack propagation K_{ID}.

Efforts during this first year focused on Tasks 1 and 4. The following paragraphs describe the progress.

Progress on Toughness Measurements for Impact-Loaded Cracks

The results of a previous AFOSR-sponsored research program defined the conditions of pulse duration and crack length for valid dynamic fracture toughness measurements. It was shown that well-established static stress intensity expressions apply to dynamic loading situations when the crack length a_o and pulse duration T_o are such that $c_1T_o/a_o > 40$, where c_1 is the longitudinal wave velocity in the specimen. These results provide the criteria necessary to design a specimen and impact device for unambiguous K_{Id} determinations.

The previous work showed further that for combinations of crack length and pulse duration satisfying the inequality $c_1T_o/a_o < 3$, the crack tip stress intensity history had a constant shape, dependent only on stress pulse amplitude and independent of crack length. Crack instability was postulated to occur if the stress intensity exceeds the dynamic fracture toughness for some (as yet poorly defined) minimum time.

Major goals of this program are to make valid K_{Id} measurements and establish minimum time conditions by using the previously gained insight into dynamic crack instability behavior. This section of the report describes specimen design considerations and efforts to obtain a suitable dynamic loading device by modifying a Charpy impact tester.

The dimensions of single-edge-notched specimens and the amplitudes of the tensile pulses required for crack instability were determined by considering the diagram in Figure 1. The diagram, which plots crack length versus the ratio of crack length and specimen width, has been constructed for a material having a K_{Id} of 50 MPa $m^{1/2}$ and for pulse durations of 17.5 μs and 70 μs. Three K-history domains were indicated: the quasi-static domain in the lower region, the crack-length-independent domain in the upper region, and a transition domain in between. Based on this diagram, a specimen 4-cm wide containing a 1-cm-long edge crack was chosen for dynamic fracture toughness determinations. To investigate minimum times for crack instability, specimens 12-cm wide containing a 6-cm-long crack will be tested. The diagram also indicates that a stress pulse amplitude of 200 MPa will be required to cause instability of short cracks.

To produce the required tensile pulse, we first examined the possibility of modifying a standard Charpy pendulum device. An anvil block was welded to the SEN specimen and two striker plates were attached to the end of the pendulum arm, Figure 2. When the striker plates impact the anvil, a tensile pulse is generated in the specimen that travels

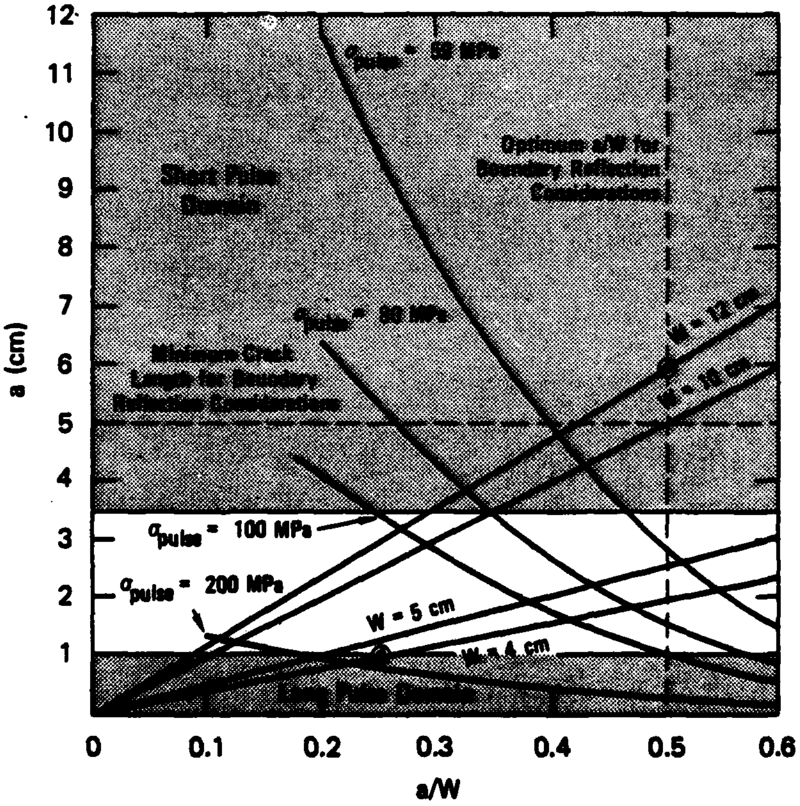

Diagram for K_{Id} = 50 MPa $m^{1/2}$ c_1 = 5845 m/s

T_{min} = 17.5 μs T_{max} = 70 μs

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FIGURE 1 DESIGN DIAGRAM FOR DETERMINING DIMENSIONS OF DYNAMIC FRACTURE SPECIMEN

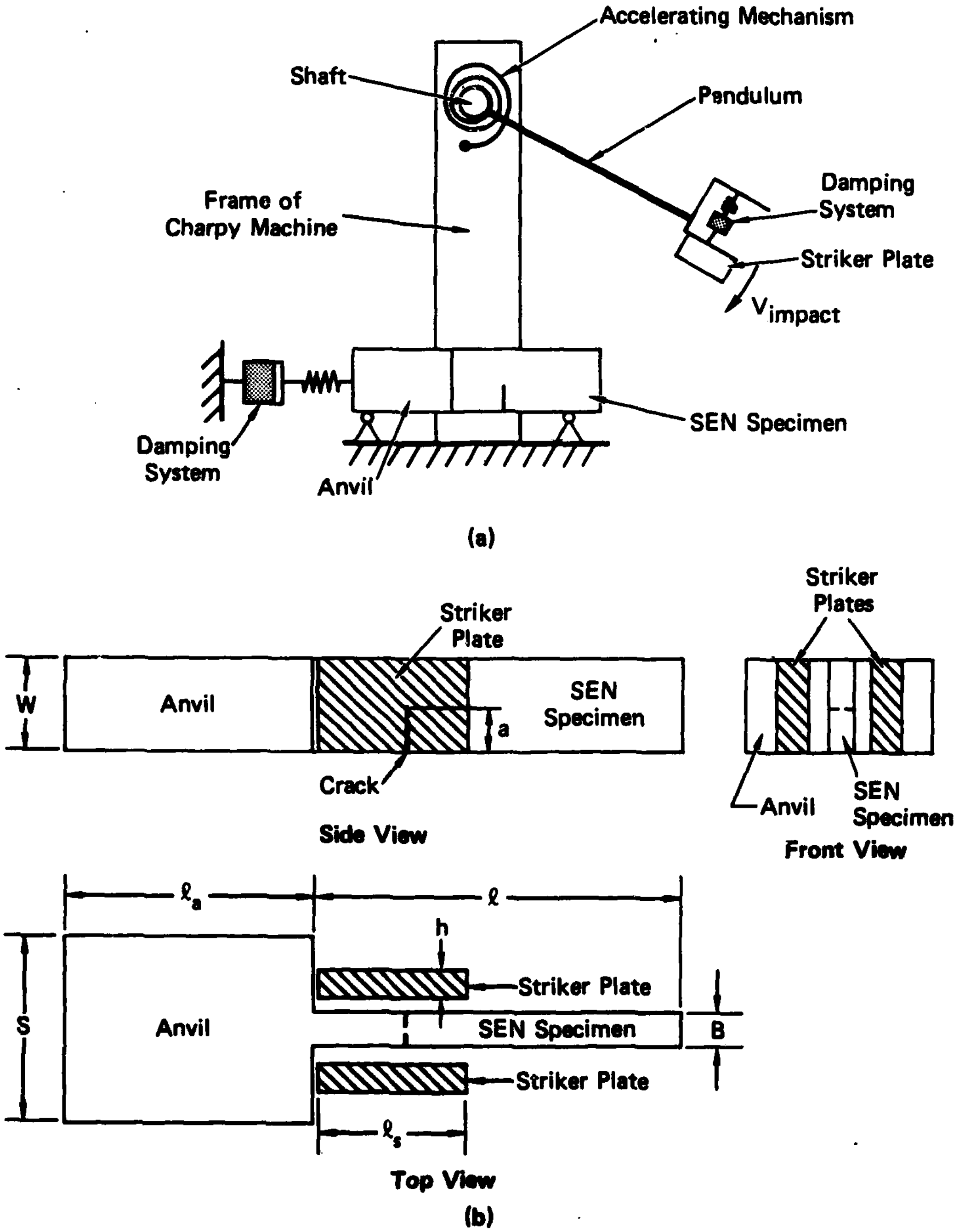

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FIGURE 2 (a) SCHEMATIC OF IMPACT DEVICE, (b) DETAIL VIEWS OF ANVIL-SPECIMEN–STRIKER PLATES SYSTEM INDICATING IMPORTANT DIMENSIONS to the crack location. Energy-absorbing material was placed at the rear of the anvil and the striker plates to reduce the amplitude of reflected waves. Two-dimensional, finite-difference code calculations were performed to aid in designing the anvil and striker plate geometries.

Based on the design criteria and the computations just discussed, an available Charpy device was modified and its ability to produce a rapid, flat-topped tensile pulse was evaluated by performing impact experiments on specimens instrumented with as many as fourteen strain gages. A stress pulse record obtained from an unnotched specimen at the crack tip location is shown in Figure 3. The tensile stress rises rapidly to about 65 MPa, falls to about 50 MPa in about 22 μs, then suddenly vanishes. Subsequent tensile pulses are not reduced in amplitude. The shape of the initial tensile stress pulse computed by the finite difference code, Figure 4, is in good agreement with the measured pulse shape.

These computations and experiments showed that a tensile pulse of a shape suitable for dynamic crack instability investigations could be obtained with this modified impact device, and that the pulse durations could be varied over the required range. However, pulse shape was very sensitive to the alignment of the striker plates and anvil, and indicated the need for a precise guiding assembly for the pendulum arm. Furthermore, pulse amplitudes will be required that are greater than those achievable by gravity forces. Higher amplitude pulses will be obtained in this next year by incorporating a torsion bar to accelerate the pendulum arm. Finally, the amplitudes of subsequent tensile pulses were observed in the experiments to be nearly equal to the initial pulse amplitude. To ensure that post-test observations of crack instability can be attributed to the initial tensile pulse, the amplitudes of subsequent pulses will be suppressed by appropriate location of the crack and specimen boundaries.

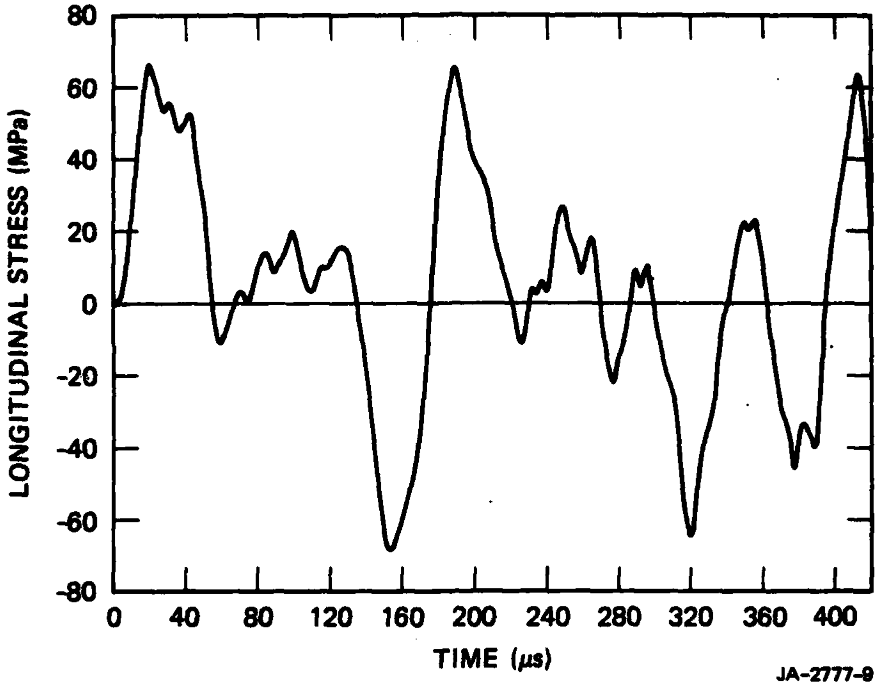

FIGURE 3 EXPERIMENTALLY RECORDED STRESS HISTORY IN SEN SPECIMEN
Impact velocity 4.5 m/s; striker length 10 cm.

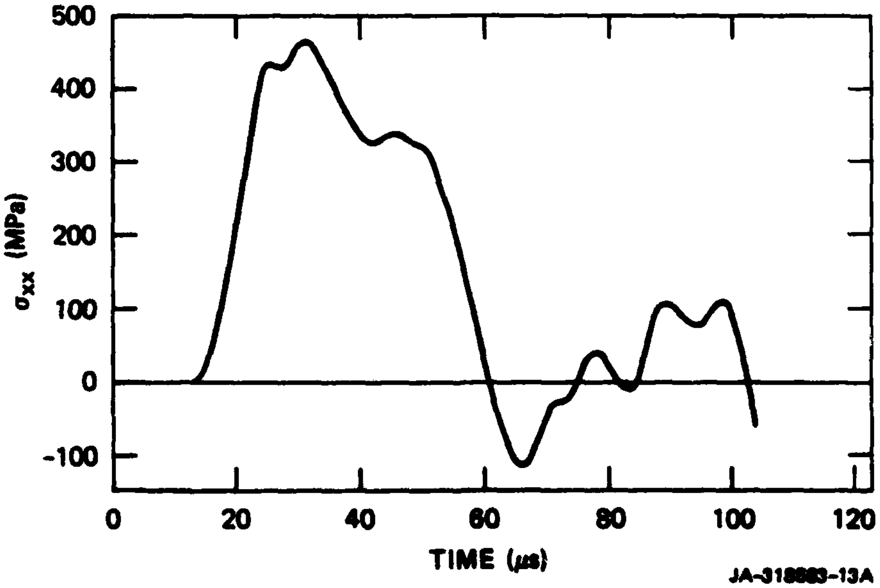

FIGURE 4 STRESS HISTORY IN SEN SPECIMEN AS COMPUTED USING WAVE PROPAGATION CODE
Impact velocity 27 m/s; striker length 10 cm.

Progress on Toughness Measurements for Fast Running Cracks

The high stresses and strains in the vicinity of a crack tip cause near crack-tip material to flow plastically, and it is this plastic deformation that governs the material's toughness or resistance to fracture. Because the energy absorbed in plastic deformation is dissipated as heat, material near to a fast-running-crack tip (quasi-adiabatic conditions) experiences slight increases in temperature. Thus, if these temperatures can be measured with sufficient spatial, temporal, and thermal resolution, the data can be used to solve the heat flow equations to compute the heat liberated by the crack, hence the energy absorbed in plastic deformation, and hence the propagation toughness K_{ID}. The objective of the work described in this section was to examine the applicability of a novel optical thermoprobe to determine toughnesses for fast running cracks.

Wieder[*] directed a monochromatic light beam onto a thin semiconductor film and showed that if the wavelength of the beam matched the absorption edge of the film, high-resolution temperature measurements could be made by monitoring the change in transmitted or reflected light intensity. To examine the applicability of this technique to dynamic fracture investigations, we vapor deposited a 4500-nm-thick CdS film onto a glass microscope slide and onto the polished surface of a steel block, and the absorption characteristics were determined as a function of wavelength in transmission and reflection, Figure 5a. The modulated structure of the absorption curve obtained in reflection is caused by interference of light reflected at the front and rear faces of the film. When the films were heated the absorption curves shifted slightly to smaller wavelengths, and this temperature sensitivity is the feature that is exploited for the thermal probe. The intensity of the light beam passing through the film changes markedly with temperature if the wavelength is on the absorption edge and hence provides a sensitive measure of the temperature.

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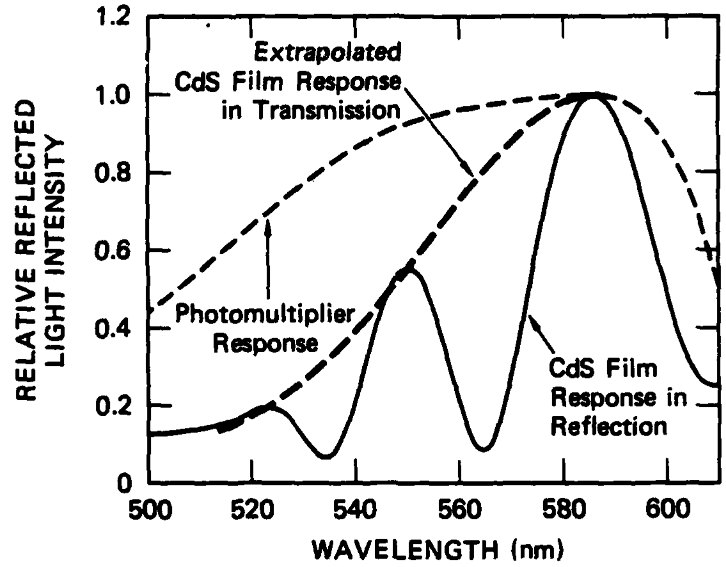
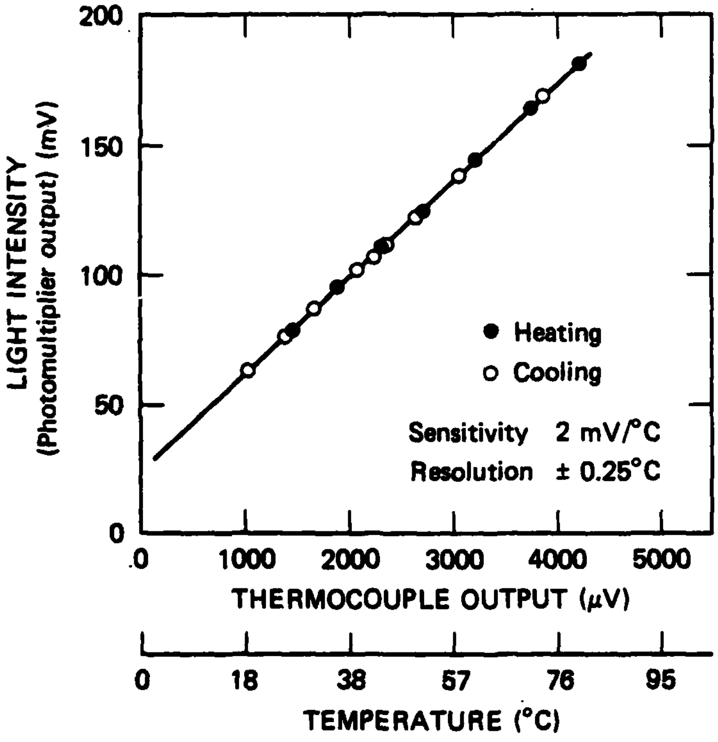
[*] H. Wieder, Optics Communications, <u>11</u> (3), 701 (1974).



(a) ABSORPTION CURVE IN THE REFLECTION MODE



(b) TEMPERATURE SENSITIVITY CURVE

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FIGURE 5 RESULTS OF CALIBRATION EXPERIMENTS ON CdS FILMS

CdS film thickness: approximately 4500 nm.

Using the steep edges caused by the interference phenomena, a linear temperature response was obtained over a range of 150°C with a resolution of 0.25°C, Figure 5b. This response appears adequate for the dynamic fracture experiments, and hence loading fixtures and compact fracture specimens have been machined in preparation for K_{ID} determinations. The experiments will be performed during the second research year.

Techniques and procedures for producing films of reproducible optical response need to be developed, and work to these ends will continue.

PUBLICATIONS AND PRESENTATIONS

Papers prepared or published and presentations made since the beginning of AFOSR sponsorship 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 (1980).

D. A. Shockey, J. F. Kalthoff, and D. C. Erlich, "Evaluation of Dynamic Crack Instability Criteria," submitted to the International Journal of Fracture.

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

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.

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, WA, 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 Werkstoffmechanik, 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 the Polish Academy of Science, the 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.

D. A. Shockey, "Simultaneous Measurements of Stress Intensity and Toughness for Fast Running Cracks in Steel," 18th Annual Meeting, Society of Engineering and Science, Brown University, Providence, RI, September 2-4, 1981.

LIST OF PERSONNEL

Dr. D. A. Shockey, Principal Investigator

Dr. J. H. Giovanola, Project Leader

Mr. H. Yamada

Dr. W. Klemm

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