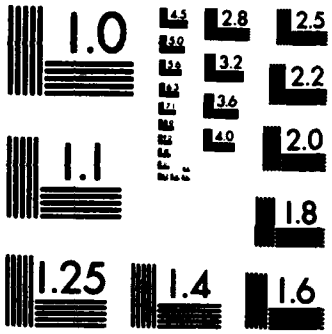
AD-A181 758 SUMMARY OF THE PROCEEDINGS OF THE NATIONAL SYMPOSIUM ON FRACTURE MECHANIC..(U) ARMY ARMAMENT RESEARCH DEVELOPMENT AND ENGINEERING CENTER WAT.. 1/1

UNCLASSIFIED J H UNDERWOOD ET AL. DEC 86 ARCCB-TR-86039 F/G 20/11 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(2)

AD

TECHNICAL REPORT ARCCB-TR-86039

DTIC FILE COPY

SUMMARY OF THE PROCEEDINGS OF THE SEVENTEENTH NATIONAL SYMPOSIUM ON FRACTURE MECHANICS

AD-A181 758

JOHN H. UNDERWOOD
RICHARD CHAIT
C. WILLIAM SMITH
DAVID P. WILHEM
WAYNE R. ANDREWS
JAMES C. NEWMAN

DTIC
ELECTE
JUN 2 2 1987
S D
E

DECEMBER 1986

US ARMY ARMAMENT RESEARCH AND DEVELOPMENT CENTER
CLOSE COMBAT ARMAMENTS CENTER
BENÉT WEAPONS LABORATORY
WATERVLIET, N.Y. 12189-4050

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

87 6

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
ARCCB-TR-86039

2. GOVT ACCESSION NO.
AD-A181 758

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
SUMMARY OF THE PROCEEDINGS OF THE SEVENTEENTH NATIONAL SYMPOSIUM ON FRACTURE MECHANICS

5. TYPE OF REPORT & PERIOD COVERED
Final

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
John H. Underwood, Richard Chait, C. William Smith, David P. Wilhem, Wayne R. Andrews, and James C. Newman (See Reverse)

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
US Army Armament Research, Develop, & Engr Center
Benet Weapons Laboratory, SMCAR-CCB-TL
Watervliet, NY 12189-4050

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
AMCMS No. 7280.12.1200.0
PRON No. 1A52NZMZ1A1A

11. CONTROLLING OFFICE NAME AND ADDRESS
US Army Armament Research, Develop, & Engr Center
Close Combat Armaments Center
Dover, NJ 07801-5001

12. REPORT DATE
December 1986

13. NUMBER OF PAGES
23

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
Published in ASTM STP 905, titled Fracture Mechanics: Seventeenth Volume.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)
Fracture Mechanics
Applications
Ductile Fracture
Test Methods
Surface Crack

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)
This report gives a brief summary of the Symposium and a more detailed description of the proceedings. A summary is given of each of the forty-four papers appearing in the proceedings. The papers are grouped into five categories used as session topics at the Symposium: applications, subcritical crack growth, fracture testing, ductile fracture, and analysis and mechanisms.

(Keyword)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

7. AUTHORS (CONT'D)

John H. Underwood
U.S. Army Armament Research, Development, and Engineering Center
Benet Weapons Laboratory
Watervliet, NY

Richard Chait
U.S. Army LABCOM
Materials Technology Laboratory
Watertown, MA

C. William Smith
Virginia Polytechnic Institute & State University
Blacksburg, VA

David P. Wilhem
Northrop Aircraft
Hawthorne, CA

Wayne R. Andrews
General Electric Company
Schenectady, NY

James C. Newman
NASA Langley Research Center
Hampton, VA

TABLE OF CONTENTS

	Page
INTRODUCTION	1
EDITOR'S COMMENTS	3
SUMMARY OF PAPERS	4
Applications	4
Subcritical Crack Growth	7
Fracture Testing	10
Ductile Fracture	13
Analysis and Mechanisms	14
APPENDIX	19

Accession For
NTIS GRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification
By
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

QUALITY INSPECTED 1

INTRODUCTION

The Seventeenth National Symposium on Fracture Mechanics was held on 7-9 August 1984 in Albany, New York. ASTM Committee E-24 on Fracture Testing was the sponsor. J. H. Underwood, US Army Armament Research, Development, and Engineering Center, served as Symposium chairman and co-editor of the proceedings. R. Chait, US Army Materials Technology Laboratory; C. W. Smith, Virginia Polytechnic Institute and State University; D. P. Wilhem, Northrop Aircraft; W. A. Andrews, General Electric Company; and J. C. Newman, NASA Langley Research Center, served as Symposium co-chairmen and co-editors of the proceedings.

The proceedings were dedicated to the following group of individuals and their pioneering work in fracture testing:

William F. Brown, Jr.
James E. Campbell
Roy H. Christensen
John Hodge
George R. Irwin
Joseph M. Krafft
William T. Lankford
John R. Low, Jr.
Richard A. Rawe
John E. Srawley
Henry J. Stremba
Charles F. Tiffany

Their important contributions were central to the ASTM Special Committee on Fracture Testing of High Strength Sheet Materials, forerunner of Committee E-24 on Fracture Testing.

As a tribute to the founders of ASTM Committee E-24 and to the series of symposia which they helped to establish, the following was offered as a special presentation at the Albany meeting.

THE 17TH SYMPOSIUM ON FRACTURE

At first a Committee, called E-24,
Studied aspects of fracture not known before;
And Irwin suggested the very best way
Was to write all the terms as functions of K.

This worked for bodies whilst still elastic,
But needed correction as the stresses turned plastic;
Till Rice and some others showed us the way
To express all the terms by the integral J.

And presently users were nothing loath
To use dJ for stable crack growth;
So fracture was thought to be well understood
At the Albany meeting of John Underwood.

But then the Symposium, in second day session,
Was taught a quite salutary lesson;
As the crucial question was faced by John Srawley
That sometimes J would serve us but poorly.

But if these complexities seem to confuse us,
Just follow the founders' advice on consensus
And study the problem until a year older,
Then tell us next time in the Conference at Boulder.

Dedicated to those founding members
of the original Committee, whom
it was my good fortune to know.

CERDIC RENRUT
9 August 1984

EDITOR'S COMMENTS

The proceedings and the Seventeenth National Symposium on Fracture Mechanics on which it is based, are part of a continuing series. These symposia have clearly become the most prestigious in the field of fracture. As such, they are the focus and forum for quality work in all areas of the field. This is the purpose of the Seventeenth Symposium and proceedings.

If the field can be divided into testing and analysis, the former has been emphasized more in the series and in the seventeenth of the series. This is appropriate, considering the sponsor, Committee E-24 on Fracture Testing. Nevertheless, analysis is a required part of any test, and much of the work reported in the proceedings is primarily analysis.

At least four general topics or categories of work frequently occur in the papers: ductile fracture, test method development, surface cracks and shape effects, and high temperature and loading rate effects. The prevalence of these four categories attests to the basic practical nature of the field of fracture and of those who work in it. Each of these categories defines an area of important current concern in the design and use of load-carrying components and structures. It is the hope and belief of all those involved that the Symposium and proceedings have contributed to these and other important areas in the field of fracture.

We take this opportunity to thank two groups who deserve a significant share of the credit for the effort. The first is the combined support staff of all of us. The administrative and clerical work of this whole group was essential to the task and is greatly appreciated. The second group is made

up of the behind-the-scenes people whose work is nonetheless critical. In particular, we thank Professor Ray Eisenstadt of Union College for his help in administering the Symposium, Mr. Jim Gallivan of the U.S. Army LABCOM, Materials Technology Laboratory, for financial support, the late Dr. Fred Schmeideshoff of the Army Research Office for his help in organizing the Symposium, and Professor Jerry Swedlow for his continuing support and sound advice during the entire process.

SUMMARY OF PAPERS

There were fifty-five presentations on the program at the Seventeenth National Symposium on Fracture Mechanics. For a variety of reasons, all related to the technical and time pressures of preparing a submission to this type of meeting and publication, forty-four appear in the proceedings. Titles and authors of these forty-four presentations are listed in the Appendix to this report. At the Symposium, the presentations were divided into five categories, which were somewhat arbitrary because of the broad scope of many papers. We used the same categories in the following summary of papers.

Applications

The papers in this section were concerned with the application of fracture mechanics concepts to analyze fatigue crack growth and fracture behavior of metallic materials and to analyze fracture behavior of ceramic and composite materials.

P. D. Hilton, R. A. Mayville, and D. C. Peirce used fracture mechanics analyses to establish the material fracture toughness requirements to avoid loss of a ship propeller blade. Using engineering approximations and a simple finite element analysis of a particular propeller crank ring, a toughness value from a J-R resistance curve was established as a minimum requirement for 4150H steel material. The fact that a full-scale laboratory test on a 4150H crank ring did not experience unstable fracture showed that the analysis was conservative.

The paper by K. Tanaka, M. Sato, T. Ishikawa, and H. Takashima presented a new wide-plate, short-crack arrest (SCA) test specimen for testing steel weld joints at low temperatures. The basic idea for the development of the SCA test is that brittle fracture should be initiated at the center of a wide plate to eliminate the effects of high compressive residual stresses that exist in welded crack-arrest specimens with edge cracks. One advantage of the SCA test is that it stimulates a surface defect which may exist in actual structures.

C. Y. Yang and W. H. Bamford characterized the response of semi-elliptical surface cracks under thermal shock conditions which may result from safety injection actuation in nuclear reactor vessels. They developed a methodology to predict the growth behavior of such cracks under simulated thermal shock conditions. Results from the study showed that cracks tend to elongate along the vessel's inside surface.

R. G. Forman and V. Shivakumar conducted fatigue crack growth tests on circumferential surface cracks in solid and hollow cylinders under remote tension and bending loads. Tests were conducted on both aluminum and titanium alloy specimens. Results show that surface crack shapes in solid cylinders can be accurately represented by a circular arc, whereas crack shapes for internal or external surface cracks in hollow cylinders can be represented by a transformed semiellipse. Stress intensity factor expressions for surface cracks in hollow cylinders were presented.

The paper by W. L. Bradley, K. E. McKinney, and P. C. Gerhardt studied the dynamic fracture behavior of ductile cast iron and cast steel using either blunt-notched or fatigue precracked (side-grooved) Charpy specimens. The blunt-notched specimens gave erroneous indications of the relative toughness of the two materials (ductile iron being quite inferior to cast steel), whereas the precracked and side-grooved specimens showed that the ductile iron was actually superior to cast steel at temperatures below ambient. The differences in these results were attributed to variations in constraint through the thickness.

The effect of loading rate on the dynamic fracture of reaction-bonded silicon nitrate (RBSN) was presented by B. M. Liaw, A. S. Kobayashi, and A. F. Emery. A novel experimental-numerical procedure, where the experimentally determined crack extension history drives a finite element code in its generation mode, was used in the study. One of the major findings was that a crack in RBSN can continue to propagate at its terminal velocity under a low dynamic stress intensity factor.

The last three papers in this section dealt with the fracture behavior of composite materials. M. M. Ratwani and R. B. Deo used the resistance curve approach to characterize the delamination growth resistance of various composite material systems. They found that the delamination growth resistance curves were a function of the resin material as well as the fiber used.

C. E. Harris and D. H. Morris compared the fracture behavior of thick graphite-epoxy laminates using the standard fracture toughness specimens (compact, three-point bend, and center-crack tension). Fracture toughness values computed using the load at the intersection of the five percent secant line with the load-COD (crack opening displacement) record were found to be independent of both laminate thickness and specimen configuration.

The paper by R. A. Simonds studied the residual strength of five boron-aluminum laminates with sharp notches with and without prior fatigue loading. Although the fatigue loading (60 to 80 percent of the static tensile strength for about 100,000 cycles) caused some matrix and fiber cracking, the residual strength was not significantly affected by the prior fatigue loading.

Subcritical Crack Growth

Most of the attention on the subject of fatigue crack propagation rates (FCPR) has been devoted to behavior at ambient temperature under constant frequency, constant amplitude conditions. This session delved deeper into the factors that influence FCPR. It also evaluated some interesting techniques for monitoring crack growth behavior.

T. Nicholas and T. Weerasooriya examined hold time effects on FCPR at elevated temperatures. Using Inconel 718 and studying the constant K behavior at 650°C, they were able to show that the hold times at maximum load displayed the greatest FCPR. Also, at maximum load hold times greater than five seconds, FCPR was time dependent. A linear cumulative damage model based solely on fatigue and sustained load data was found to be adequate for spectrum loading as long as the hold times were at maximum load. Also evaluating Inconel 718 at 650°C, A. Petrovich, W. Bessler, and W. Ziegler were able to detail the interactive effects of low and high frequency cycling on FCPR. It is interesting that as high frequency ΔK is combined with constant low frequency ΔK, two regions of FCPR behavior were noted; one where low frequency cycles dominate and the other where high frequency cycling governs. In the former, a retardation effect which is strongly dependent on low cycle ΔK was noted.

A. Saxena studied crack growth under high temperature nonsteady-state conditions. He described a crack parameter C_t which correlated well with da/dt under conditions that range from small scale creep to the steady-state creep regime. The correlation appears to be independent of specimen geometry. It was shown that, for A470 class 8 steel, da/dt as a function of C_t is independent of temperature in the range of 482°C to 538°C to a first order approximation.

I. Soya, H. Takashima, and Y. Tanaka addressed the fatigue behavior of welded Invar sheets in the cryogenic temperature region. An equivalent

stress intensity factor, Keq, was calculated from $(K_I^2 + K_{II}^2)^{1/2}$ and was based on a finite element analysis of elastic and elastic-plastic conditions that exist at the weld root. Keq, plotted versus the number of cycles to failure, can be utilized in the same manner as the traditional S-N curve. In the temperature range between room temperature and -162°C for several types of fillet joints and one type of seam weld, it was shown that Keq can be used to normalize the cycles-to-failure data in the region where large plastic deformation is not a factor.

Several novel techniques for monitoring crack growth behavior complemented the efforts noted above. J. M. Larsen reported the development of an automated photomicroscope system for monitoring the initiation and growth of small surface cracks. Behavior of surface cracks in the 25 μm to 2000 μm size range was studied. Ti-6Al-2Sn-4Zr-6MO (Ti-6246) was used to evaluate the system which had a precision of about 1 μm for cracks of about 25 μm in length. It is noted that this method can provide a cost effective means of monitoring growth of small cracks.

The growth and coalescence of small cracks was the subject of a paper by A. F. Grandt, A. B. Thakker, and D. E. Tritsch. A multiple degree-of-freedom algorithm was utilized to predict the growth of separate cracks. The crack shapes and sizes are then allowed to develop naturally as they join into a single flaw. The analysis was confirmed through the use of heat tinting techniques on both Waspalloy and Ti-6246 alloys.

W. N. Sharpe, Jr. and J. J. Lee described an experimental study of crack tip displacement during high temperature cyclic loading of Inconel 718. At the heart of the technique is a laser-based interferometer that detects fringe patterns produced from two microhardness indentations. Tests conducted between 23°C and 650°C showed that compliances were in reasonable agreement with analytical predictions. Opening load ratios were found to be independent of temperature, crack length, and precracking level when measured at positions more than half the specimen thickness away from the crack tip.

R. E. Wilson and A. N. Palazotto also concentrated on crack-tip behavior utilizing IN-100 compact tension specimens cycled at 732°C. Viscoplastic constitutive equations were utilized in an analysis of the stress and strain field around the crack tip. It was interesting to note that most of the plastic straining occurs within the first three cycles and after about 23 cycles the material will no longer undergo any more plastic strain increase. After one to three cycles, the strain field ahead of the crack remains relatively constant.

Fracture Testing

The following papers were included in Session III of the Symposium, held on Wednesday, 8 August 1984, to honor Dr. John E. Srawley and Mr. William F. Brown, Jr. In their long association with NASA Lewis Research Center, these two researchers made a truly significant contribution to the area of fracture mechanics test methods. This session, which they chaired, was a tribute to them as they ended their full-time work in the field of fracture.

The first three papers described opening mode fracture toughness testing using new test geometries. In the paper by J. H. Underwood, J. A. Kapp, and M. D. Witherell, recommendations were given for practical arc bend specimen geometries. Solutions were presented for stress intensity, crack mouth displacement, and load-line displacement for fracture specimens that were compared using finite element and boundary collocation techniques.

J. A. Kapp and W. J. Bilinsky described J_{Ic} tests in aluminum and steel alloys using the new arc-tension specimen and the existing compact specimen. A Merkle-Corten type analysis was presented for calculating J for the new specimen. The results showed that the specimen and methods of J analysis are suitable for accurate determination of J_{Ic}, and it is suggested that this information be added to the ASTM J_{Ic} test method.

The paper by J. H. Giovanola showed the influence of specimen dimensions and impact velocity on dynamic fracture toughness of an edge-cracked coupon loaded in bending by impact at midsection. This new procedure was used to measure the toughness of 4340 steel at three loading rates. The relative advantages of this one-point bend test in dynamic fracture are indicated.

Two papers were presented on Mode II fracture testing. R. J. Buzzard, B. Gross, and J. E. Srawley described a test specimen that was developed to obtain fatigue crack propagation data under Mode II shear loading. Stress intensity factor and displacement analyses were performed and compared with photoelastic stress analysis. These results and the nature of the observed fatigue crack growth data suggested that the specimen and analysis would be adequate for Mode II fatigue testing.

The paper by L. Banks-Sills and M. Arcan used a finite element analysis of a compact K_{II} specimen and load frame geometry to determine Mode II critical stress intensities. Mode II toughness tests of polymethyl methacrylate (PMMA) indicated that K_{Ic} was greater than K_{IIc} and that the average Mode II crack extension angle occurred along the direction of maximum tangential stress, which was between 63 to 70 degrees.

The last three papers in Session III dealt with J-R curve testing. The paper by G. E. Sutton and M. G. Vassilaros presented comparative data for J-integral resistance curves for ASTM Class C and 3-Ni steels, using two reference techniques, multispecimen and DC potential drop, for comparison with elastic compliance. The J-R curves established using elastic compliance showed no significant difference from the reference curve data. In the paper by P. H. Davies and C. P. Stearns, the DC potential drop technique was shown to be unacceptable for measuring the fracture toughness of Zircaloy-2 in the brittle-ductile fracture transition. The potential drop underestimated crack extension by 60 percent, increasing to 100 percent at higher test temperatures. Reproducible results were obtained using individual specimen calibrations. J. A. Kapp and M. I. Jolles performed J-R tests of two aluminum and three steel alloys using Charpy size bend specimens and larger, standard compact specimens. Both load drop and electric potential methods of crack growth were used. Based on comparisons of results from the two types of specimens and crack growth, the load drop method with small bend specimens resulted in approximate J-R curves which would be suitable for quality control fracture toughness tests.

Ductile Fracture

There were two general groups of papers in this session of the Symposium, one emphasizing test methods and results, and the second emphasizing the mechanisms of ductile fracture.

In the first group, K. Hirano, H. Kobayashi, and H. Nakazawa described a single specimen ultrasonic method for obtaining J versus crack growth curves. Measurements of both J_{Ic} and tearing modulus in A533B steel were found to be independent of specimen geometry. It was also observed that the crack tip opening displacement (CTOD) remained nearly constant during stable crack growth. M. G. Vassilaros, R. A. Hays, and J. P. Gudas obtained J-R curves using compact specimens from A106 steel pipe and compared the results with those from four-point bend tests of four-foot lengths of eight-inch diameter pipe. The general result of the comparison was that the small specimen tests do not directly predict the J-R curve behavior of full size pipe because of the small amount of crack growth available in the specimen tests. O. L. Towers and S. J. Garwood described J-integral and CTOD analyses of bend tests of HY130 steel. Since these are the two most accepted methods of analysis for ductile fracture, this comparison of results is particularly interesting. In general, the two methods agree in their description of resistance to ductile tearing. Both methods indicate greater tearing resistance for shallower cracks, that is, for a/W of 0.1 to 0.2 compared with 0.5.

Four papers dealt primarily with ductile fracture mechanisms. M. R. Etemad and C. E. Turner investigated ductile tearing mechanisms, using experiments with HY130 and analyses of both energy rate, I, and tearing

modulus, dJ/da. In the authors' words, "Subject to the choice of appropriate compliance terms, the experimental behavior is predicted satisfactorily by both I and dJ/da methods." The authors also stated that satisfactory predictions are restricted to the geometry for which the R-curve was obtained. J. E. Carifo, J. L. Swedlow, and C.-W. Cho discussed finite element computation of stable crack growth using techniques of element node release. Conditions for nodal release are described and demonstrated in a series of finite element models of stable crack growth. E. M. Hackett, P. J. Moran, and J. P. Gudas investigated environmentally assisted crack growth of 4340 steel in seawater using techniques developed for the study of stable elastic-plastic crack growth. They found that J-R curves could be used for this different purpose, provided that the rate dependence of the environmentally controlled process is considered. They observed a significant (fourfold) decrease in the energy required for crack initiation, J_{Ic}, due to cathodic polarization of the specimens. T. J. Watson and M. I. Jolles investigated global plastic energy dissipation for crack initiation and growth using experiments with HY130 steel for a variety of specimen configurations. Specimen size, specimen type, crack length, and side grooving were studied. R-curves using plastic energy dissipation (rather than J) showed some geometry dependence, which was minimized using side grooves.

Analysis and Mechanisms

The papers presented on the last day of the Symposium focused primarily upon determination of loading and geometric (body shape) effects upon fracture parameters, or upon determination of near tip material response.

Included in this session was an overview lecture by Dr. George Irwin on "Progressive Fracture Mechanics," in which he traced developments over several decades up to the present time. The range of time and technical topic in the lecture covered all aspects of fracture, including analyses, experiments, and applications.

The first paper of the session was that of S. L. Pu, which addressed the problem of an array of unequal depth radial cracks at the inner radius of a pressurized cylinder. He used quadrilateral finite elements and collapsed singular elements around the crack tip to calculate stress intensity factor for a number of cases. The general result was that a crack which was slightly deeper than others in the array had a significantly higher K value, so the deeper crack quickly dominated.

G. T. Sha and C.-T. Yang described a method for computing stress intensity factors by combining the uncracked stress field with explicit crack-face weight functions through superposition. The method was illustrated by applying it to the problem of symmetric radial cracks emanating from a circular hole in a plate.

J. F. Yau presented a surface crack solution for fatigue crack propagation analysis of notched components. The solution was based on the weight function technique, and it was compared with a wide range of test results. Good agreement was observed between experimental results and analytical predictions, including such key information as stress intensity factor, crack propagation rate, residual life, and variation in crack shape.

H. M. Müller, S. Müller, D. Munz, and J. Neumann presented results of an analytical and experimental study of surface crack growth under cyclic loading. They found that use of local ΔK values gave a poor prediction of the crack aspect ratio, while use of a weighted average ΔK or a crack closure factor improved predictions. W. G. Reuter presented results of a combined analytical-experimental study of crack growth initiation under both elastic and plastic conditions. A modified center-cracked panel equation was used in the predictions, and acoustic emission methods were used to detect the load corresponding to crack initiation. The author presented evidence which questions the usefulness of J_{Ic} in structures where J-controlled fields are not attainable.

P. Balladon and J. Heritier compared the fracture toughness and crack growth properties of three grades (316L, 347, and austeno-ferritic) of steel at both room temperature and elevated temperatures. Comparisons were based on the J-integral concept. Variations observed could not be explained solely on the basis of inclusion content and crack plane orientation.

H. Homma, D. A. Shockey, and S. Hada performed experiments in steel and aluminum to measure the minimum time duration at load which is required before a crack grows in an unstable manner. The relation between the minimum times obtained for the materials and their mechanical properties was discussed. The experimental results showed that the minimum time is longer for the more ductile materials. A. Shukla and S. Anand reported on the results of dynamic photoelastic experiments under remote biaxial stress fields. They found that while the normal stress parallel to the crack

surface had negligible influence on the branching stress intensity factor and crack velocity, a strong influence of the parallel stress was observed on the branching angle.

T. L. Anderson and S. Williams used the results of a large number of crack tip opening displacement (CTOD) measurements on carbon manganese steels (using both single-edge notch bending and tensile tests) to assess the dominant mechanism for size effects on CTOD values in the ductile-brittle transition region. They concluded that, under conditions of small-scale yielding, a high constraint statistical sampling model works well for explaining size effects. However, when net section yielding occurs, statistical effects are suppressed and size effects are dominated by constraint effects. J. A. Joyce and E. M. Hackett described a series of J-integral R-curve tests on three-point bend steel specimens at three different load rates. Through the use of multispecimen and key curve procedures at the higher rates, they found that both J_{IC} values and tearing modulus (T) values were elevated at the higher loading rates. The J_{IC} and T values were increased by a factor of approximately two for a loading rate increase of six orders of magnitude.

C. W. Smith, J. S. Epstein, and O. Olaosebikan presented a quantitative evaluation of the loss of the inverse square root singularity when a crack intersects a free surface at right angles in nearly incompressible materials. Compact bending and surface flaw specimens were tested using both frozen stress photoelasticity and moire interferometry. After correlating free surface results with analytical results, they measured the variation of the

lowest eigenvalue through the thickness and found thicker transition zones than previously suspected.

The session was closed with a paper by I. S. Raju and J. C. Newman in which they utilized a refined three-dimensional finite element model to study surface flaws. They employed singularity elements along the crack front and linear stress elements elsewhere to obtain the stress intensity distribution along flaws in pipes and rods under both extension and bending. Results from the models, which contained 6500 degrees of freedom, compared favorably with analyses and experiments of others.

APPENDIX

PROCEEDINGS OF THE SEVENTEENTH NATIONAL SYMPOSIUM ON FRACTURE MECHANICS

Applications

An Application of Fracture Mechanics to a Ship Controllable Pitch Propeller Crank Ring - P. D. Hilton, R. A. Mayville, and D. C. Peirce

A New Wide Plate Arrest Test (SCA Test) on Weld Joints of Steels for Low Temperature Application - K. Tanaka, M. Sato, T. Ishikawa, and H. Takashima

Variable Flaw Shape Analysis for a Reactor Vessel Under Pressurized Thermal Shock Loading - C. Y. Yang and W. H. Bamford

Growth Behavior of Surface Cracks in the Circumferential Plane of Solid and Hollow Cylinders - R. G. Forman and V. Shivakumar

Fracture Toughness of Ductile Iron and Cast Steel - W. L. Bradley, K. E. McKinney, and P. C. Gerhardt, Jr.

Effect of Loading Rate on Dynamic Fracture of Reaction Bonded Silicon Nitride - B. M. Liaw, A. S. Kobayashi, and A. F. Emery

Resistance Curve Approach to Composite Materials Characterization - M. M. Ratwani and R. B. Deo

A Comparison of the Fracture Behavior of Thick Laminated Composites Utilizing Compact Tension, Three-Point Bend, and Center-Cracked Tension Specimens - C. E. Harris and D. H. Morris

Residual Strength of Five Boron/Aluminum Laminates With Crack-Like Notches After Fatigue Loading - R. A. Simonds

Subcritical Crack Growth

Hold-Time Effects in Elevated Temperature Fatigue Crack Propagation - T. Nicholas and T. Weerasooriya

Interactive Effects of High and Low Frequency Loading on the Fatigue Crack Growth of Inconel 718 - A. Petrovich, W. Bessler, and W. Ziegler

Creep Crack Growth Under Non-Steady-State Conditions - A. Saxena

An Application of Stress Intensity Factor to Fatigue Strength Analysis of Welded Invar Sheet for Cryogenic Use - I. Soya, H. Takashima, and Y. Tanaka

An Automated Photomicroscopic System for Monitoring the Growth of Small Fatigue Cracks - J. M. Larsen

An Experimental and Numerical Investigation of the Growth and Coalescence of Multiple Fatigue Cracks at Notches - A. F. Grandt, Jr., A. B. Thakker, and D. E. Tritsch

Near-Tip Crack Displacement Measurements During High-Temperature Fatigue - W. N. Sharpe, Jr. and J. J. Lee

Viscoplastic Fatigue in a Superalloy at Elevated Temperatures - R. Wilson and A. Palazotto

Fracture Testing

Fracture Testing With Arc Bend Specimens - J. H. Underwood, J. A. Kapp, and M. D. Witherell

J_{Ic} Testing Using Arc-Tension Specimens - J. A. Kapp and W. J. Bilinsky

Investigation and Application of the One-Point-Bend Impact Test - J. H. Giovanola

Mode II Fatigue Crack Growth Specimen Development - R. J. Buzzard, B. Gross, and J. E. Srawley

A Compact Mode II Fracture Specimen - L. Banks-Sills and M. Arcan

Influence of Partial Unloadings Range on the J_I-R Curves of ASTM A106 and 3-Ni Steels - G. E. Sutton and M. G. Vassilaros

Fracture Toughness Testing of Zircaloy-2 Pressure Tube Material With Radial Hydrides Using Direct-Current Potential Drop - P. H. Davies and C. P. Stearns

Assessment of J-R Curves Obtained From Precracked Charpy Specimens - J. A. Kapp and M. I. Jolles

Ductile Fracture

A Single Specimen Determination of Elastic-Plastic Fracture Resistance by Ultrasonic Method - K. Hirano, H. Kobayashi, and H. Nakazawa

J-Resistance Curve Analysis for ASTM A106 Steel 8-Inch Diameter Pipe and Compact Specimens - M. G. Vassilaros, R. A. Hays, and J. P. Gudas

Influence of Crack Depth on Resistance Curves for Three-Point Bend Specimens in HY130 - O. L. Towers and S. J. Garwood

An Investigation of the I and dJ/da Concepts for Ductile Tearing Instability - M. R. Etemad and C. E. Turner

Computation of Stable Crack Growth Using the J-Integral - J. E. Carifo, J. L. Swedlow, and C.-W. Cho

Evaluation of Environmentally Assisted Cracking of a High Strength Steel Using Elastic-Plastic Fracture Mechanics Techniques - E. M. Hackett, P. J. Moran, and J. P. Gudas

Plastic Energy Dissipation as a Parameter to Characterize Crack Growth - T. J. Watson and M. I. Jolles

Analysis and Mechanisms

Stress Intensity Factors for a Circular Ring With Uniform Array of Radial Cracks of Unequal Depth - S. L. Pu

Weight Functions of Radial Cracks Emanating From a Circular Hole in a Plate - G. T. Sha and C.-T. Yang

An Empirical Surface Crack Solution for Fatigue Propagation Analysis of Notched Components - J. F. Yau

Extension of Surface Cracks During Cyclic Loading - H. M. Müller, S. Muller, D. Munz, and J. Neumann

Comparison of Predicted Versus Experimental Stress for Initiation of Crack Growth in Specimens Containing Surface Cracks - W. G. Reuter

Comparison of Ductile Crack Growth Resistance of Austenitic, Niobium-Stabilized Austenitic, and Austeno-Ferritic Stainless Steels - P. Balladon and J. Heritier

Minimum Time Criterion for Crack Instability in Structural Materials - H. Homma, D. A. Shockey, and S. Hada

Dynamic Crack Propagation and Branching Under Biaxial Loading - A. Shukla and S. Anand

Assessing the Dominant Mechanism for Size Effects on CTOD Values in the Ductile-to-Brittle Transition Region - T. L. Anderson and S. Williams

Dynamic J-R Curve Testing of a High Strength Steel Using the Key Curve and Multispecimen Techniques - J. A. Joyce and E. M. Hackett

Boundary Layer Effects in Cracked Bodies: An Engineering Assessment - C. W. Smith, J. S. Epstein, and O. Olaosebikan

Stress Intensity Factors for Circumferential Surface Cracks in Pipes and Rods Under Tension and Bending Loads - I. S. Raju and J. C. Newman

TECHNICAL REPORT INTERNAL DISTRIBUTION LIST

	NO. OF COPIES
CHIEF, DEVELOPMENT ENGINEERING BRANCH	
ATTN: SMCAR-CCB-D	1
-DA	1
-DP	1
-DR	1
-DS (SYSTEMS)	1
-DC	1
-DM	1
CHIEF, ENGINEERING SUPPORT BRANCH	
ATTN: SMCAR-CCB-S	1
-SE	1
CHIEF, RESEARCH BRANCH	
ATTN: SMCAR-CCB-R	2
-R (ELLEN FOGARTY)	1
-RA	1
-RM	1
-RP	1
-RT	1
TECHNICAL LIBRARY	5
ATTN: SMCAR-CCB-TL	
TECHNICAL PUBLICATIONS & EDITING UNIT	2
ATTN: SMCAR-CCB-TL	
DIRECTOR, OPERATIONS DIRECTORATE	1
DIRECTOR, PROCUREMENT DIRECTORATE	1
DIRECTOR, PRODUCT ASSURANCE DIRECTORATE	1

NOTE: PLEASE NOTIFY DIRECTOR, BENET WEAPONS LABORATORY, ATTN: SMCAR-CCB-TL, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST

	NO. OF COPIES
ASST SEC OF THE ARMY RESEARCH & DEVELOPMENT ATTN: DEP FOR SCI & TECH THE PENTAGON WASHINGTON, D.C. 20315	1
COMMANDER DEFENSE TECHNICAL INFO CENTER ATTN: DTIC-DOA CAMERON STATION ALEXANDRIA, VA 22314	12
COMMANDER US ARMY MAT DEV & READ COMD ATTN: DRCDE-SG 5001 EISENHOWER AVE ALEXANDRIA, VA 22333	1
COMMANDER ARMAMENT RES & DEV CTR US ARMY AMCCOM ATTN: SMCAR-FS	1
SMCAR-FSA	1
SMCAR-FSM	1
SMCAR-FSS	1
SMCAR-AEE	1
SMCAR-AES	1
SMCAR-AET-O (PLASTECH)	1
SMCAR-MSI (STINFO) DOVER, NJ 07801	2
DIRECTOR BALLISTICS RESEARCH LABORATORY ATTN: AMXBR-TSB-S (STINFO) ABERDEEN PROVING GROUND, MD 21005	1
MATERIEL SYSTEMS ANALYSIS ACTV ATTN: DRXSY-MP ABERDEEN PROVING GROUND, MD 21005	1
COMMANDER US ARMY AMCCOM ATTN: SMCAR-ESP-L ROCK ISLAND, IL 61299	1
COMMANDER ROCK ISLAND ARSENAL ATTN: SMCRI-ENM (MAT SCI DIV) ROCK ISLAND, IL 61299	1
DIRECTOR US ARMY INDUSTRIAL BASE ENG ACTV ATTN: DRXIB-M ROCK ISLAND, IL 61299	1
COMMANDER US ARMY TANK-AUTMV R&D COMD ATTN: TECH LIB - DRSTA-TSL WARREN, MI 48090	1
COMMANDER US ARMY TANK-AUTMV COMD ATTN: DRSTA-RC WARREN, MI 48090	1
COMMANDER US MILITARY ACADEMY ATTN: CHMN, MECH ENGR DEPT WEST POINT, NY 10996	1
US ARMY MISSILE COMD REDSTONE SCIENTIFIC INFO CTR ATTN: DOCUMENTS SECT, BLDG. 4484 REDSTONE ARSENAL, AL 35898	2
COMMANDER US ARMY FGN SCIENCE & TECH CTR ATTN: DRXST-SD 220 7TH STREET, N.E. CHARLOTTESVILLE, VA 22901	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET WEAPONS LABORATORY, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.

TECHNICAL REPORT EXTERNAL DISTRIBUTION LIST (CONT'D)

	NO. OF COPIES
COMMANDER US ARMY LABCOM MATERIALS TECHNOLOGY LAB ATTN: SLCMT-IML WATERTOWN, MA 01272	2
COMMANDER US ARMY RESEARCH OFFICE ATTN: CHIEF, IPO P.O. BOX 12211 RESEARCH TRIANGLE PARK, NC 27709	1
COMMANDER US ARMY HARRY DIAMOND LAB ATTN: TECH LIB 2800 POWDER MILL ROAD ADELPHIA, MD 20783	1
COMMANDER NAVAL SURFACE WEAPONS CTR ATTN: TECHNICAL LIBRARY CODE X212 DAHLGREN, VA 22448	1

	NO. OF COPIES
DIRECTOR US NAVAL RESEARCH LAB ATTN: DIR, MECH DIV	1
CODE 26-27, (DOC LIB) WASHINGTON, D.C. 20375	1
COMMANDER AIR FORCE ARMAMENT LABORATORY ATTN: AFATL/MN	1
AFATL/MNG EGLIN AFB, FL 32542-5000	1
METALS & CERAMICS INFO CTR BATTELLE COLUMBUS LAB 505 KING AVENUE COLUMBUS, OH 43201	1

NOTE: PLEASE NOTIFY COMMANDER, ARMAMENT RESEARCH, DEVELOPMENT, AND ENGINEERING CENTER, US ARMY AMCCOM, ATTN: BENET WEAPONS LABORATORY, SMCAR-CCB-TL, WATERVLIET, NY 12189-4050, OF ANY ADDRESS CHANGES.

END

7-87

DTIC