

Fatigue and Fracture Mechanics

28TH
VOLUME

John H. Underwood,

Bruce D. Macdonald, and

Michael R. Mitchell, editors



STP 1321

STP 1321

Fatigue and Fracture Mechanics: 28th Volume

*John H. Underwood, Bruce D. Macdonald,
and Michael R. Mitchell, editors*

ASTM Publication Code Number (PCN):
04-013210-30



ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959

Printed in the U.S.A.

ISBN: 0-8031-2410-4
PCN: 04-013210-30
ISSN: 1040-3094

Copyright © 1997 AMERICAN SOCIETY FOR TESTING AND MATERIALS, West Conshohocken, PA. All rights reserved. This material may not be reproduced or copied, in whole or in part, in any printed, mechanical, electronic, film, or other distribution and storage media, without the written consent of the publisher.

Photocopy Rights

Authorization to photocopy items for internal, personal, or educational classroom use, or the internal, personal, or educational classroom use of specific clients, is granted by the American Society for Testing and Materials (ASTM) provided that the appropriate fee is paid to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923; Tel: 508-750-8400; online: <http://www.copyright.com/>.

Peer Review Policy

Each paper published in this volume was evaluated by two peer reviewers and at least one editor. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

To make technical information available as quickly as possible, the peer-reviewed papers in this publication were prepared "camera-ready" as submitted by the authors.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of the peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution of time and effort on behalf of ASTM.

Foreword

This publication, *Fatigue and Fracture Mechanics: 28th Volume*, contains papers presented at the 28th National Symposium on Fatigue and Fracture Mechanics, held in Saratoga Springs, New York, on 25–27 June 1996. The sponsor of the event was ASTM Committee E-08 on Fatigue and Fracture and the Army Research Office. The symposium chairmen were John H. Underwood, U.S. Army Armament R D & E Center, Bruce D. Macdonald, Knolls Atomic Power Laboratory, and Michael R. Mitchell, Rockwell International Science Center.

Contents

Overview

ix

JERRY L. SWEDLOW MEMORIAL LECTURE

The Merging of Fatigue and Fracture Mechanics Concepts: A Historical Perspective—J. C. NEWMAN, JR.

3

GENERAL TOPICS

Effect of Interfacial Characteristics on Mode I Fracture Behaviour of Glass Woven Fabric Composites Under Static and Fatigue Loading—

HIROYUKI HAMADA, MASAYA KOTAKI, AND ADRIAN LOWE

55

Application of Fracture Mechanics in Maintenance of High Temperature Equipment—An assessment of Critical Needs—ASHOK SAXENA

70

On Space Flight Pressure Vessel Fracture Control—JAMES B. CHANG

86

An X-Ray Diffraction Study of Microstructural Deformation Induced by Cyclic Loading of Selected Steels—PATRICK M. FOURSPRING AND

ROBERT N. PANGBORN

105

Progressive Damage and Residual Strength of Notched Composite Laminates: A New Effective Crack Growth Model—LIN YE, AKBAR AFAGHI-KHATIBI,

AND YIU-WING MAI

123

Fracture Toughness Results and Preliminary Analysis for International Cooperative Test Program on Specimens Containing Surface

Cracks—WALTER G. REUTER, NORMAN C. ELFER, D. ALLAN HULL,

JAMES C. NEWMAN, JR., DIETRICH MUNZ, AND TINA L. PANONTIN

146

Influence of Pre-Strain on Fracture Toughness and Stable Crack Growth in Low Carbon Steels—TAKASHI MIYATA, TETSUYA TAGAWA, AND SYUJI AIHARA

167

CONSTRAINT EFFECTS

3-D Constraint Effects on Models for Transferability of Cleavage Fracture Toughness—ROBERT H. DODDS, JR., CLAUDIO RUGGIERI, AND

KYLE KOPPENHOEFER

179

Estimation of Lower-Bound K_{Ic} on Pressure Vessel Steels from Invalid Data —DONALD E. MCCABE AND JOHN G. MERKLE	198
Fracture of Surface Cracks Loaded in Bending —Y. J. CHAO AND W. G. REUTER	214
Ductile-to-Brittle Transition Characterization Using Surface Crack Specimens Loaded in Combined Tension and Bending —JAMES A. JOYCE AND RICHARD E. LINK	243
Application of Small Specimens to Fracture Mechanics Characterization of Irradiated Pressure Vessel Steels —MIKHAIL A. SOKOLOV, KIM WALLIN, AND DONALD E. MCCABE	263
Single Specimen Method for Determining the Master Curve in the Transition —JOHN D. LANDES AND KHALLED SAKALLA	280
Application of J-Q Theory to the Local Approach Statistical Model of Cleavage Fracture —CHENG YAN, SHANG-XIAN WU, AND YIU-WING MAI	296
Analysis of Stable Tearing in a 7.6 mm Thick Aluminum Plate Alloy —D. S. DAWICKE, R. S. PIASCIK, AND J. C. NEWMAN, JR.	309
FATIGUE TECHNOLOGY	
Fatigue Technology in Ground Vehicle Design —RONALD W. LANDGRAF	327
Service Load Fatigue Testing of Railway Bogie Components —GARY MARQUIS, TORMOD DAHLE, AND JUSSI SOLIN	342
Some Methods of Representing Fatigue Lifetime as a Function of Stress Range and Initial Crack Size —ANTHONY P. PARKER AND JOHN H. UNDERWOOD	355
Development of a Rapid Thermomechanical Fatigue Test Method —THOMAS S. COOK AND HSIN T. HUANG	370
Stress Concentration, Stress Intensity and Fatigue Lifetime Calculations for Shrink-Fit Compound Tubes Containing Axial Holes Within the Wall —STEPHEN N. ENDERSBY, ANTHONY P. PARKER, TIMOTHY J. BOND, AND JOHN H. UNDERWOOD	385
Fatigue Analysis of a Vessel Experiencing Pressure Oscillations —EDWARD TROIANO, JOHN H. UNDERWOOD, ANTHONY SCALISE, PETER O'HARA, AND DANIEL CRAYON	397
Fatigue Crack Growth in the Highly Plastic Regime —K. S. KIM AND Y. M. BAIK	411

WELD APPLICATIONS

- Fracture Initiation by Local Brittle Zones in Weldments of Quenched and Tempered Structural Alloy Steel Plate**—KEVIN L. KENNEY,
WALTER G. REUTER, HAROLD S. REEMSNYDER, AND DAVID K. MATLOCK 427
- Effect of Weld Metal Mismatch on Joint Efficiency and Measured Fracture Toughness**—RICHARD YEE, LALIT MALIK, AND JACK MORRISON 450
- Inference Equations for Fracture Toughness Testing: Numerical Analysis and Experimental Verification**—YONG-YI WANG, HAROLD S. REEMSNYDER, AND MARK T. KIRK 469
- Fracture Assessment of Weld Material from a Full-Thickness Clad RPV Shell Segment**—JANIS A. KEENEY, B. RICHARD BASS, AND WALLACE J. MCAFEE 485
- Incorporation of Residual Stress Effects into Fracture Assessments Via the Finite Element Method**—PANAGIOTIS MICHALERIS, MARK KIRK,
WILLIAM MOHR, AND TOM MCGAUGHY 499
- Analysis of Unclad and Sub-Clad Semi-Elliptical Flaws in Pressure Vessel Steels**—HUGO IRIZARRY-QUÍÑONES, BRUCE D. MACDONALD, AND
WALLACE J. MCAFEE 515

FRACTURE ANALYSIS

- Predicting Crack Instability Behaviour of Burst Tests from Small Specimens for Irradiated Zr-2.5Nb Pressure Tubes**—PAULINE H. DAVIES 535
- Predicting Fracture Behavior of Aluminum Alloys**—ANTHONY T. CHANG AND JENNIFER A. CORDES 562
- The Effect of Crack Instability/Stability on Fracture Toughness of Brittle Materials**—FRANCIS I. BARATTA 577
- Hydrogen Induced Cracking Tests of High Strength Steels and Nickel-Iron Base Alloys Using the Bolt-Loaded Specimen**—G. N. VIGILANTE,
J. H. UNDERWOOD, D. CRAYON, S. TAUSCHER, T. SAGE, AND E. TROIANO 602
- Computer Simulation of Fast Crack Propagation and Arrest in Steel Plate with Temperature Gradient based on Local Fracture Stress Criterion**—SUSUMU MACHIDA, HITOSHI YOSHINARI, AND SHUJI AIHARA 617
- Stress Intensity Magnification Factors for Fully Circumferential Cracks in Valve Bodies (Thick Cylinders)**—PIR M. TOOR 641
- K3D—A Program for Determining Stress Intensity Factors of Surface and Corner Cracks from a Hole**—WEI ZHAO, MICHAEL A. SUTTON, AND
JAMCS C. NEWMAN, JR. 656

**Finite Element Analysis on the Fracture of Rubber Toughened Polymer
Blends—YISHENG WU, JINGSHEN WU, AND YIU-WING MAI**

671

Indexes

685

Overview

The 28th National Symposium on Fatigue and Fracture Mechanics included research and application papers on a broad range of fatigue and fracture topics to match the intended wide scope of the symposium. Thirty-seven papers are published here on topics including general overview papers, constraint effects on fracture toughness, technology and applications of fatigue, weld applications, and analysis of fracture in various materials and components. These five topics were used to group the papers, but it is clear that there is considerable overlap of these topics in many of the papers.

The National Symposium on Fatigue and Fracture Mechanics has become an annual review of new research and technology in this broad technical area for presentation and discussion before leading practitioners in fatigue and fracture from the United States and abroad. Much of the work is included in this archival publication following a thorough peer review process. Many basic concepts and results in fatigue and fracture are well understood and have been documented in prior technical literature, so that the problems now being addressed are often the difficult and complex questions. Nearly every paper here addresses an unproven material or manufacturing process or a set of severe service conditions that requires very careful testing or analysis. To the extent that the problems and solutions are complex, this Symposium and its papers are intended for those who have some experience with the field of fatigue and fracture. Nevertheless, the introductory and reference materials contained in the papers can be used by those with less experience to gain some understanding of sub-topics within the overall field. In addition, the three keynote papers and the many papers dealing with industrial applications will also be useful for those with limited experience in fatigue and fracture.

General Topics

The Jerry L. Swedlow Memorial Lecture by J. C. Newman, Jr. of NASA Langley Research Center opened the Symposium with a critical review of the past four decades of technical development of fatigue and fracture mechanics concepts. Included are discussions on the development of fatigue damage and crack formation and growth concepts, crack growth analysis, material inhomogeneities and nonlinear behavior, crack-closure mechanisms, small crack growth behavior, and safe-life and damage-tolerance concepts. Hamada et al. studied the influence of fiber surface treatment on the Mode I delamination toughness and fatigue resistance of glass fabric/vinyl ester composite laminates. The static toughness of the laminates before treatment showed consistent differences in the two main fabric directions. Treatment with high concentrations of aqueous silane solutions increased both the fatigue resistance and the static fracture toughness of the laminates. Saxena gave a critical assessment of the state-of-the-art of time-dependent fracture mechanics concepts, tests and analysis procedures—particularly in relationship to maintenance of high-temperature equipment. Creep deformation and time-dependent damage accumulation in components subjected to elevated temperature were emphasized. Chang described the results of a research program conducted to establish the fracture control requirements for composite overwrap pressure vessels used in space programs. Important findings include fatigue and fracture analysis

methods for metallic liners, nondestructive evaluation techniques, and impact damage effects on the composite overwrap.

Fourspring and Pangborn (in a student paper) used X-ray diffraction to characterize cyclic microstructural deformation in polycrystalline steels. They studied the distribution of deformation at certain fractions of fatigue life and at various surface and interior locations of fatigue samples. Changes in deformation were noted for different levels of cycling and at different locations. Ye et al. modeled damage initiation and growth at holes and notches in fiber-reinforced metal laminates and polymer matrix composite laminates. Damage and damage growth were modeled using fictitious cracks with a cohesive stress acting on the crack surfaces. The effect of hole/notch size on residual strength of the laminates was determined from the models and compared with experimental results from the literature. Reuter et al. report the results of an international cooperative test program on fracture toughness of high-strength steel specimens containing surface cracks. It was determined that the maximum load cannot be used to calculate toughness when significant stable cracking occurs. However, the load at which stable cracking initiates, obtained by NDT methods, provided a useful comparison to K_{Ic} . Miyata et al. investigated a relationship for upper shelf fracture toughness degradation of low-carbon steel due to cold working. The product of yield stress and critical strain for microvoid coalescence (based on material tests and the HRR model) is related to J_{Ic} . The critical strain is also correlated with the slope of the tearing resistance curve.

Constraint Effects

Nine contributions deal with constraint effects on transition regime and upper shelf fracture toughness of structural alloys, a general topic of active fracture mechanics research in recent years. In the Session Keynote Paper by Dodds et al. from the University of Illinois, Urbana, micro-mechanics modeling of material failure near the crack front is combined with constraint modeling through finite element analysis to examine constraint effects on ductile tearing. J - T and J - Q analyses are used to describe stationary crack stress fields. The advantages and limitations of this approach in correlating fracture toughness data are described. McCabe and Merkle describe a computational procedure that couples order statistics, weakest link statistics, and a constraint model to determine a lower bound value of fracture toughness. This approach is utilized when data are too sparse to use conventional statistics.

Two papers deal with constraint effects in surface-cracked configurations. Chao and Reuter compare surface and through-crack fracture toughness results for high-strength D6-AC steel. Strains at a critical distance ahead of the crack front were related to K and T -stress in a data set of bend specimens with through cracks. Initiation sites and fracture loads were predicted for a second data set containing surface flaws. Joyce and Link used surface-cracked specimens loaded in combined tension and bending to characterize the transition regime of ASTM A515 Grade 70 steel. Three-dimensional elastic-plastic finite element analysis was used to determine the maximum value of J along the crack front at fracture. Comparison was made with previous results from the same alloy tested in different configurations.

Sokolov et al. compared precracked Charpy-size-corrected results for irradiated and unirradiated reactor vessel steel with results from large specimen databases. The master curve placement from the small specimens agreed with the large specimen EPRI and ASME data fits. This work supports the use of surveillance Charpy specimens to define the irradiation damage transition temperature shift in fracture mechanics terms. Landes and Sakalla developed a technique to estimate the fracture mechanics transition temperature from a single specimen. Order statistics were used to generate a single temperature fracture distribution. This led to an estimate of fracture mechanics transition temperature with a 20°C scatter for

sets of six specimens taken one at a time. Yan et al. used a simplified local damage statistical approach, in conjunction with the J - Q stress field, to account for scatter in transition regime fracture toughness of structural steel. Use of the J - Q stress field removes the need for large deformation finite element calculations that are generally needed to determine the effective stress used in the local damage approach. Dawicke et al. performed a numerical and experimental study of thickness effects on stable tearing of 2324-T7351 aluminum alloy. Three-dimensional elastic-plastic finite element modeling of side-grooved compact tension specimens was performed. The crack tip opening angle results were compared with those from microtopographic experiments to support a steady state ductile tearing fracture criterion.

Fatigue Technology

Four of the seven papers in the fatigue technology grouping deal with applications, and the remainder have to do with assessment of certain types of fatigue behavior. Applications include the session keynote paper on ground vehicle design, railway components, and cannon components. Assessments of fatigue behavior include methods for representing lifetime, thermomechanical test methods, and crack growth in fully plastic conditions.

The Session Keynote Paper by Landgraf of Virginia Polytechnic Institute reviews the development and implementation of fatigue technology in automotive design. Examples are given, including the complexities of real engineering structures and service environments, along with probabilistic approaches for dealing with variability and uncertainty. Marquis et al. describe the results of a series of fatigue tests on railway boggie components in Finland and Sweden, with attention to the relationship between test loads and the actual field service loads. Results showed that design and testing should include the large amount of fatigue damage that can be contributed by the small cycles in the loading spectrum. Parker and Underwood describe an analysis that represents fatigue lifetime as a single expression which is a simple function of local stress range and initial crack size. Existing experimental life data are used to define the expression, and examples are given of its application to the ordering of several potential fatigue failure locations within a complex cannon component. Cook and Huang describe the development of a rapid thermomechanical fatigue test method for application to the hot components of a gas turbine. They use an integrated air-cooling-induction heating chamber for developing the test method. The test equipment and the associated heat transfer analysis and stress analysis required to analyze the test data are described.

Endersby et al. present elastic-plastic numerical analysis and fatigue lifetime predictions for shrink-fit compound thick cylinders containing multiple, axial holes at the interface between the inner and outer tube. As the shrink-fit interference is increased, the fatigue lifetime increases, and the axial holes become the critical location rather than the bore of the inner tube. The lifetime is superior to that of autofrettaged compound tubes with similar axial holes. Troiano et al. describe a fatigue and fracture case study of a prototype cannon pressure vessel that failed prematurely following cannon firings that involved both pressure oscillations and an aggressive chemical environment. Analysis showed that most of the pressure oscillation cycles were below the fatigue threshold, and environmental cracking was the more likely cause of the premature failure. Kin and Baik evaluate the elevated temperature fatigue cracking behavior of nickel base Alloy 718 under plastic loading conditions, using ΔK and ΔJ correlations of crack growth rate. At 538°C, ΔK gives the better description of growth rate, whereas at 649°C the description is poor for both approaches. Finite element analysis shows that crack closure diminishes as the crack tip plasticity increases.

Weld Applications

Welding adds considerable complexity to the already difficult fracture mechanics problems associated with flaw tolerance assessment of structural alloys. The six papers on weld applications address some of these complexities, including weld inhomogeneities, weld/base metal strength mismatch, residual stresses, and shallow and irregularly shaped flaws at welds.

Kenney et al. (in a student paper) showed that structural steel multi-pass weld cross sections demonstrate considerable variation in fracture toughness. In particular, the coarse-grain heat-affected zone may include brittle zones that seriously degrade the resistance to fracture initiation. The nature of these regions of limited cleavage resistance and the comparison with superior weld regions provide a compelling argument to adhere to recommended interpass temperatures. Yee et al. suggest that mismatching base metal and weld strength can affect joint efficiency and the applicability of standard fracture toughness test methods. To test these hypotheses, 15-mm-thick HSLA-100 steel plate was heat treated to various strength levels and joined with the same weld wire and process. For yield strength mismatches from -30% to $+16\%$, bend specimens showed no significant variation in weld toughness in either the transition regime or upper shelf. Cross-weld tensile testing revealed no loss of joint efficiency for yield strength mismatches greater than -9% . Wang et al. presented improvements in J -integral and CTOD formulas used to interpret test results with various weld/base metal strength mismatch. The range of applicability of the formulas was extended to $0.05 < a/w < 0.7$. Results were checked by comparing the predicted residual plastic component of CTOD with that from interrupted fracture toughness tests.

Keeney et al. describe finite-element analyses of full-thickness weld-cladding beam test specimens containing through-clad flaws. A description of the test program is provided. Comparison is made with previous analyses of unclad, flawed beams. Michaleris et al. show how undue conservatism regarding weld residual stresses can be overcome by finite element simulation of the weld process. Redistribution and relaxation of stresses during ductile crack growth were also modeled. Weld process simulation temperatures agreed with thermocouple data, and predicted residual stresses agreed with measurements from test components. Irizarry-Quinones et al. investigated flawed beams with and without weld cladding, using both numerical calculations and experiments to quantify weld-cladding benefits to crack driving force. Three-dimensional elastic-plastic finite element analysis included cooling from stress relief heat treatment and modeling the resulting tensile residual stress in the cladding due to its different thermal expansion. Stress intensity factor solutions were found to agree with the finite element solution up to complete yielding of the cladding.

Fracture Analysis

The remaining eight papers in the volume address computational and experimental analysis of fracture for application to a variety of materials and structural components. Included are papers dealing with fracture critical applications such as nuclear reactors and cannon barrels, calculation of stress intensity factors for general application, analysis of fracture in general classes of materials such as aluminum alloys and brittle materials, and fracture of specific materials such as a brittle steel with a thermal gradient and a rubber-toughened polymer.

Davies determined critical crack lengths for nuclear reactor pressure tubes using small-scale curved compact tension specimens. These small-scale test results were compared with results from other small-scale tests of different configuration. Scaling factors based on a

volume-controlled fracture model for the deformation J -integral were key to these studies. Chang and Cordes describe a computational model for predicting fracture in flawed or cracked specimens of aluminum alloys. Finite element calculations using nonlinear spring elements are used to predict the crack initiation load, the extent of material damage, and the crack growth behavior. No experimental fracture toughness data are required to make fracture predictions, only material tensile stress-strain data. Baratta summarizes three experimental works by him and other authors that investigate the effects of crack stability on the measured values of fracture toughness—in a brittle polymer, a brittle tungsten alloy, and a silicon nitride ceramic. Comparisons of the experimental results with his stability analysis show that stable fracture resulted in a lowering of the measured K_{Ic} for the three materials. Vigilante et al. (in a student paper) conducted hydrogen-cracking tests on high-strength steels and nickel-iron base alloys using a bolt-load specimen in acid and electrolytic cell environments. In general the steels showed much higher crack growth rates and thresholds than the nickel-iron base alloys. In both material types strength level was the predominant factor in controlling cracking, with a 10% increase in strength often causing a drastic decrease in cracking resistance.

Machida et al. proposes a fracture mechanics model for dynamic elastic-plastic crack propagation and arrest based on Achenbach's asymptotic singular stress field approach. The model simulates acceleration, deceleration, and arrest of a crack in a wide plate in biaxial tension with a temperature gradient (ESSO wide plate test). They conclude that the crack arrest toughness is heavily dependent on the temperature gradient. Toor presents stress intensity solutions from a finite element analysis that accounts for the curvature effects of circumferential cracks at the inner surface of thick wall cylinders. Results are given for a wide range of cylinder radius to wall thickness ratio and crack depth to wall thickness ratio. Zhao et al. showed that damage tolerance analysis of surface and corner cracks emanating from holes can be implemented by a three-dimensional weight function method. The K3D computer program can be run on a personal computer to determine the stress intensity factor along the entire crack front in complicated (uncracked) stress fields. Wu et al. investigated the effects of rubber particles on the constitutive relation and the fracture toughness of polymers. Stress analysis showed that the hydrostatic stress inside the particles is similar to that in the matrix, whereas rubber particle cavitation releases the constraint and allows significant plastic strain to occur.

Acknowledgments

We thank Dr. Kalisam Iyer and the Army Research Office for financial support for the Symposium. We thank the authors for their efforts in presenting and publishing their technical work. The student authors and their sponsors deserve special thanks:

Patrick M. Fourspring	Lockheed Martin Corporation, KAPL Inc.
Kevin L. Kenney	Idaho National Engineering Laboratory
Gregory N. Vigilante	Army Armament RD&E Center

Finally, we pay great tribute to the technical reviewers of these papers. They take the time to provide thoughtful comments and suggestions, with no thought of remuneration or rec-

ognition. There is no question that the technical quality of this volume has been significantly raised by the efforts of the peer reviewers.

John H. Underwood

Army Armament RD&E Center,
Watervliet, NY 12189;
Symposium Chairman and Editor

Bruce D. Macdonald

Knolls Atomic Power Laboratory,
Schenectady, NY 12301;
Symposium Chairman and Editor

Michael R. Mitchell

Rockwell International Science Center,
Thousand Oaks, CA 91358;
Symposium Chairman and Editor

ISBN 0-8031-2410-4