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TECHNICAL REPORT ARCCB-TR-90033

REVIEW OF ASTM SYMPOSIUM ON SURFACE CRACK GROWTH: MODELS, EXPERIMENTS, AND STRUCTURES

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NOVEMBER 1990

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1. REPORT NUMBER ARCCB-TR-90033	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REVIEW OF ASTM SYMPOSIUM ON SURFACE CRACK GROWTH: MODELS, EXPERIMENTS, AND STRUCTURES		5. TYPE OF REPORT & PERIOD COVERED Final 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) W.G. Reuter, J.H. Underwood, and J.C. Newman (See Reverse)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army ARDEC Benet Laboratories, SMCAR-CCB-TL Watervliet, NY 12189-4050		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 72801212 PRON No. AWOTS009AW1A
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army ARDEC Close Combat Armaments Center Picatinny Arsenal, NJ 07806-5000		12. REPORT DATE November 1990 13. NUMBER OF PAGES 14
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 1060, Surface Crack Growth: Models, Experiments and Structures.

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

Crack Growth
Surface Crack
Numerical Analysis
Fatigue
Fracture
Pressure Vessels

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

An overview of the ASTM Symposium on Surface Cracks: Models, Experiments, and Structures, held on 25 April 1988 in Sparks, Nevada, is presented. The background and objective for the symposium are described and the technical papers presented and published in the proceedings are summarized. The papers are in two general categories: (a) results of analytical models and experiments of surface-cracked specimens and components subjected to monotonic loading, and (b) experiments and analyses of fatigue-crack growth of surface cracks.

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DEDICATION

This report and the ASTM publication that is reviewed are dedicated to the memory of the late Professor J. L. Swedlow of Carnegie Mellon University, a world leader in the field of fracture mechanics and an authority in the area of surface crack analysis.

INTRODUCTION

Over the past thirty years, substantial effort has been devoted to developing techniques and standards for measuring fracture toughness and subcritical crack growth. These methods use specimens containing two-dimensional (2-D), through-thickness flaws because of their relative ease of fabrication and the availability of accepted analytical and numerical solutions. However, many defects observed in practice, and often responsible for failures or questions regarding structural integrity, are three-dimensional (3-D) surface flaws. The efficiency of data generated from standard specimens containing 2-D defects in predicting crack growth behavior of 3-D flaws, including crack initiation, subcritical crack growth, and unstable fracture, is a major concern. An important alternative is to use data obtained from surface-flawed specimens. Resolving these issues is a goal of the activities within Subcommittee E-24.01 on Fracture Mechanics Test Methods, a subcommittee of ASTM E-24 on Fracture Testing.

The first significant review of the status of research conducted on surface cracks was the ASME symposium "The Surface Crack: Physical Problems and Computational Solutions" organized by the late Professor J. L. Swedlow in 1972 (ref 1). The review presented here is the culmination of a joint effort of ASTM Committee E-24 and the Society for Experimental Mechanics, initiated in 1986, to identify the international state-of-the-art of research on surface flaws. The joint effort has resulted in two symposia. Papers from the first symposium, held at the Fall 1986 Society for Experimental Mechanics meeting in Keystone, Colorado, were published in 1988 in the journal Experimental Mechanics (refs 2 and 3).

The papers summarized in this report were presented at a symposium held at the Spring 1988 ASTM E-24 meeting in Sparks, Nevada and published in an ASTM Special Technical Publication (ref 4). This work describes much of the state-of-the-art research being conducted on the behavior of surface flaws.

SUMMARY OF SYMPOSIUM

The papers included in the symposium and proceedings cover: (a) analytical and numerical models for stress-intensity factor solutions, stresses, and displacements around surface cracks; (b) experimental determination of stresses and displacements due to applied loads under either predominately elastic-stress conditions or elastic-plastic conditions; and (c) experimental results related to fatigue-crack growth. The subject matter is very broad, ranging from linear-elastic fracture mechanics (LEFM) to nonlinear-elastic fracture mechanics, and includes weldments and composites. Areas where additional research is needed are also identified. For example, considerable progress has been made on the comparison of fatigue-crack growth rates, but a number of questions are still unanswered. Also, the ability to accurately predict the behavior of a surface crack is generally limited to predominately elastic-stress conditions; considerable research is required for surface cracks under elastic-plastic conditions.

The titles and authors of the papers are as follows, in two broad technical areas:

Models and Experiments--Monotonic Loading

- A Surface Crack Review: Elastic and Elastic-Plastic Behavior--D.M. Parks
- Evaluation of Finite-Element Models and Stress-Intensity Factors for Surface Cracks Emanating from Stress Concentrations--P.W. Tan, I.S. Raju, K.N. Shivakumar, and J.C. Newman, Jr.

- Tabulated Stress-Intensity Factors for Corner Cracks at Holes Under Stress Gradients--R. Perez, A.F. Grandt, Jr., and C.R. Saff

- Fracture Analysis for Three-Dimensional Bodies with Surface Crack--L. Yingzhi

- On the Semi-Elliptical Surface Crack Problem: Detailed Numerical Solutions for Complete Elastic Stress Fields--A.F. Blom and B. Andersson

- Analysis of Optical Measurements of Free-Surface Effects on Natural Surface and Through Cracks--C.W. Smith, M. Rezvani, and C.W. Chang

- Optical and Finite-Element Investigation of a Plastically Deformed Surface Flaw Under Tension--J.C. Olinkiewicz, H.V. Tippur, and F.P. Chiang

- Extraction of Stress-Intensity Factor from In-Plane Displacements Measured by Holographic Interferometry--J.W. Dally, C.A. Sciammarella, and I. Shareef

- Fracture Behavior Prediction for Rapidly Loaded Surface-Cracked Specimens --M.T. Kirk and E.M. Hackett

- Measurements of CTOD and CTOA Around Surface-Crack Perimeters and Relationships Between Elastic and Elastic-Plastic CTOD Values-- W.G. Reuter and W.R. Lloyd

- Surface Cracks in Thick Laminated Fiber Composite Plates--S.N. Chatterjee

- Surface Crack Analysis Applied to Impact Damage in a Thick Graphite/Epoxy Composite--C.C. Poe, Jr., C.E. Harris, and D.H. Morris

Fatigue-Crack Growth

- Experimental Evaluation of Stress-Intensity Solutions for Surface Flaw Growth in Plates--D.K. Carter, W.R. Canda, and J.A. Blind

- A Novel Procedure to Study Crack Initiation and Growth in Thermal Fatigue Testing--N.J. Marchand, W. Dorner, and B. Ilschner

- Observations of Three-Dimensional Surface Flaw Geometries During Fatigue Crack Growth in PMMA--W.A. Troha, T. Nicholas, and A.F. Grandt, Jr.

- Some Special Computations and Experiments on the Surface Crack Growth--M. Prodan and J.C. Radon

- Influences of Crack Closure and Load History on Near-Threshold Crack Growth Behavior in Surface Flaws--J.R. Jira, D.A. Nagy, and T. Nicholas

- Growth of Surface Cracks Under Fatigue and Monotonically Increasing Load --L. Hodulak

- Experimental Investigation of Subcritical Growth of a Surface Flaw--M. Ramulu

- Measurement and Analysis of Surface Cracks in Tubular Threaded Connections--A. Newport and G. Glinka

- Propagation of Surface Cracks in Notched and Unnotched Rods--M. Caspers, C. Mattheck, and D. Munz

- Theoretical and Experimental Analyses of Surface Cracks in Weldments--X. Niu and G. Glinka

Some of the critical areas addressed in the volume are (a) differences in constraint for 2-D through-thickness cracks and 3-D surface cracks; (b) applicability of J_{Ic}, K_{Ic}, crack-tip-opening displacement (CTOD), and da/dN test data obtained from 2-D cracks to surface cracks; and (c) applicability of surface-crack testing and analysis to composites, ceramics, and weldments. This overview briefly describes the state-of-the-art in this technical area, as well as identifies the researchers presently pursuing specific topics. Descriptions of the papers in the proceedings are given in the following sections.

MODELS AND EXPERIMENTS--MONOTONIC LOADING

The first two papers are reviews of the important numerical analysis procedures that have been applied to the surface-crack problem. Parks describes a variety of surface-crack analysis methods, including crack-front variation of K for elastic conditions and J-integral for nonlinear conditions, and line-spring and plastic-hinge models of surface-cracked pipes. He identifies two areas in need of further study, crack-tip blunting and its effect on shear deformation through to the back surface, and free surface effects on the loss of constraint for shallow cracks. Tan, Raju, Shivakumar, and Newman evaluate the finite-element methods and results for the common and difficult problem of a surface crack at a stress concentration, such as a hole. Values of K are calculated for a variety of geometries using both nodal force and virtual crack-closure methods. A related configuration is also analyzed, that of a surface crack at a semicircular edge notch in a tensile-loaded plate, for comparison with "benchmark" results obtained in the United States and abroad for this geometry.

Three papers then continue the emphasis on numerical stress analysis of surface-crack configurations to obtain crack-front K values. Perez, Grandt, and Saff use a weight-function method and finite-element results from prior work to obtain tabular results for a variety of configurations of the corner crack at a hole. They describe a superposition method which can be used to analyze problems with very complex stress fields. Yingzhi uses a high order 3-D finite-element method to calculate K for surface-crack configurations with tension and bending loads. The calculations require fewer degrees of freedom than prior work in the literature, and the results agree well with that work. Blom and Andersson use the p-version of the finite-element method to calculate the elastic-stress field in surface-cracked plates with different values of Poisson's ratio. The emphasis is on the intersection of the surface crack with the free surface. The problem becomes more complex near the free surface and for Poisson's ratio near 0.5.

The next three papers involve aspects of optical stress analysis applied to the surface-crack problem. Smith, Rezvani, and Chang describe photoelastic stress freezing tests of naturally-grown through-thickness and surface cracks in bending specimens. Their tests and associated analysis are used to study the difficult problem of free-surface effects. As in Blom and Andersson's work, complexities arise, possibly because the photoelastic results are not "sufficiently close to the free surface." The paper by Olinkiewicz, Tippur, and Chiang combines moire and finite-element methods to obtain the deformation fields of a plastically-deformed surface crack loaded in tension. The authors evaluate J from both experimental results and finite elements and find that they are essentially equivalent. Dally, Sciammarella, and Shareef use holographic interferometry and Westergaard series analyses to determine stresses and displacements around a surface crack. The experimentally-determined singularity of the stress field (of K) at the free surface is found to be close to, but in excess of, 0.5, in agreement with some analytical results from the literature. Kirk and Hackett investigate dynamic loading of surface-cracked specimens. They compare results from drop-tower-loaded, through-cracked, bend specimens containing deep and shallow cracks to results from dynamically-loaded, shallow, surface-cracked specimens, all of embrittled high strength steel. The critical J at failure for shallow, through cracks gives good predictions of surface-crack behavior, whereas the critical J for deep, through cracks underpredicts the surface-crack results.

Reuter and Lloyd describe a comprehensive experimental study of CTOD, crack-tip-opening angle (CTOA), and crack growth for tension-loaded A710 steel plates with surface cracks of various configurations. They compare their results to center-of-rotation models and numerical solutions of CTOD around the crack front. Good agreement between experimental and numerical CTOD values is demonstrated. Relationships between CTOD and CTOA and between CTOA and crack growth are also described.

The last two papers of the section on monotonic models and experiments involve surface cracks in composite materials. Chatterjee describes analysis of surface cracks in transversely isotropic and orthotropic composites and gives correction factors to obtain K for these composite types from isotropic K results from the literature. He also compares the results of test data from the literature for thick laminated fiber composites with analytical predictions for failure. The outermost layers of many composites with surface cracks are observed to fail first, unlike similar configurations in metals. Poe, Harris, and Morris describe predictions of residual strength of thick graphite/epoxy laminates using surface-crack analysis. Impact damage in this material is represented by a semielliptical surface crack of the same width and depth as the damaged area of broken fibers; the crack plane is nearly perpendicular to the fiber direction. Following a first stage of failure, well-predicted by surface-crack analysis, a second stage of failure occurs in which damaged layers delaminate from undamaged layers. The second stage failure is predicted using a maximum strain failure criterion.

FATIGUE-CRACK GROWTH

Over the past decade, the concept of correlating stress-intensity factor range, ΔK against fatigue-crack growth rate, has been shown to work quite well for 3-D crack configurations under constant amplitude loading. In order to extend these concepts to more complex loadings and to other structural configurations, much more research is needed to characterize the behavior of surface cracks. The papers in this section extend the application of LEFM concepts to the study of fatigue-crack growth of surface cracks in a wide variety of materials and in several structural configurations. The materials covered include aluminum alloys, a titanium alloy, two superalloys, polymethyl methacrylate (PMMA) and a variety of steels. In several applications, the alternating current potential drop (ACPD) technique was used to monitor the growth of surface cracks and an interferometric-displacement technique was used to monitor crack-surface profiles. The nature of the surface crack, however, is truly three dimensional. In through-thickness cracks, one may be able to use a single value of stress intensity and a single crack-opening stress to correlate fatigue-crack growth rates, but for surface cracks the 3-D variations around the crack front must be considered. Two numerical methods are used in these papers to calculate stress-intensity factor variations. They are the finite-element and weight-function methods. A knowledge of the variation of stress-intensity factors and triaxial constraint conditions around the crack front is necessary to develop improved life and strength predictions for surface cracks. The papers in this section are grouped into four topic areas, stress-intensity factor evaluations during fatigue-crack growth, 3-D crack closure and constraint, small crack behavior, and applications.

Several papers compare crack growth rates for surface cracks and those of either compact or bend specimens. Carter, Canda, and Blind evaluate several stress-intensity factor solutions for surface cracks and correlate fatigue-crack growth rate data with compact specimen data on an aluminum alloy. For a given stress-intensity factor range, their rates are well within a factor of two. The slope of their ΔK versus rate curve from their surface-crack data, however, is different than the slope from the compact specimen data. The data agree in magnitude around 12 MPa $m^{1/2}$. Their surface cracks tend to show the presence of a "cusp" where the crack intersects the plate surface. They find, however, that the Raju-Newman stress-intensity factor equations predict surface-crack growth and crack-shape changes reasonably well compared with experimental results. Prodan and Radon, using a novel method of comparing surface-crack growth with compact specimen data, also make a similar conclusion on a fine-grain structural steel. Caspers, Mattheck, and Munz make stress-intensity factor calculations for surface cracks in cylindrical bars under tension and bending loads using a weight-function method. In contrast to point values of stress-intensity factors, they evaluate the "local average" technique proposed by Cruse and Besuner. Fatigue-crack growth rate measurements made on a chromium-molybdenum steel compare very well with rates measured on four-point notch bend specimens (rates generally within about 30 percent).

Jira, Nagy, and Nicholas find that crack growth rate data measured on surface cracks and on compact specimens correlate well for a titanium alloy using a closure-based K_{eff}. They determined crack-opening loads from compliance measurements made at the crack mouth using a laser-interferometry displacement gauge. The effective stress-intensity factor range correlates data quite well for the four types of load histories used to reach a threshold condition. Using a transparent polymer (PMMA), Troha, Nicholas, and Grandt observe three different closure behaviors for surface-cracked specimens. During loading, a surface crack would open first at the maximum depth location. At a slightly higher load, the crack-mouth region would then open. This opening load produces the least amount of scatter on a K_{eff} versus rate correlation compared to two other definitions of opening load. The crack-front region at the plate surface would be the last region to open. These distinct behaviors are, in part, caused by the 3-D constraint developed around the surface-crack front. Plane-strain conditions around the maximum depth location cause lower opening loads compared to the plane-stress regions where the crack intersects the plate surface. A discussion of these constraint variations around the crack front is presented by Hodulak. The triaxiality or constraint factor presented by Hodulak is defined as the ratio of the hydrostatic stress to the effective (von Mises) stress. A knowledge of this constraint factor, or other constraint factors with other definitions, as a function of crack size, crack shape, and loading is needed to predict fatigue-crack-closure behavior and subsequent crack growth, and to predict the location of fracture initiation around a 3-D crack configuration.

Marchand, Dorner, and Ilschner use an advanced ACPD system to study crack initiation and growth under cyclic thermal histories in two superalloys. The initiation of microcracks, 10 to 50 μ_m long, could be detected. The specimen used in this study is a double-edged wedge specimen simulating the leading and trailing edges of a gas turbine airfoil. Ramulu describes the initiation and growth of small cracks in "keyhole" compact specimens of an aluminum alloy. This specimen is a standard compact specimen with a hole drilled at the end of the starter notch. Indents (about 250 μ_m deep) are made at the center of the notch root to act as crack starters. A scanning electron microscope is used to perform fractographic analyses of striation spacings to determine the growth rates for small cracks. The classical "small" crack effect is observed, i.e., the small cracks show initial rapid growth with a minimum rate occurring at about 1 to 2 mm of crack growth.

The remaining papers in this section are concerned with the application of surface-crack methodology to cracks in threaded connections and in welded joints made of steel. Newport and Glinka describe tests and analyses on surface cracks in tubular threaded connections, while Niu and Glinka describe tests and analyses on surface cracks in T-butt welded joints. The experimental and analytical approaches are nearly the same in these papers. An advanced ACPD technique is used to monitor the growth of surface cracks (both depth and length). A weight-function method (proposed by Petroski and Achenbach) is employed to calculate the stress-intensity factors for surface cracks in structural configurations. A comparison is made between theoretical and experimentally-determined stress-intensity factors. Experimental stress intensities are determined from measured rates and ΔK versus rate curves are presented. For butt-weld cracks the theoretical and experimental values compare quite well, but the values for threaded connection cracks show some large differences. Several reasons are given for the large differences: there is a lack of suitable crack growth rate data for the test specimen material; local stress concentrations at the thread root are strongly dependent upon thread load and preload on the cylinder; and the weight-function method was derived for a flat plate.

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