Overview

Over the past 30 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-the-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 use of data obtained from surface flawed specimens. Resolving these issues is a goal of activities within Subcommittee E24.01 on Fracture Mechanics Test Methods, a subcommittee of ASTM E24 on Fracture Testing.

The first significant review of the status of research being conducted on surface cracks was the ASME symposium "The Surface Crack: Physical Problems and Computational Solutions" organized by Professor J. L. Swedlow in 1972. The review presented here is the culmination of a joint effort of ASTM E24 and SEM (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 SEM meeting in Keystone, Colorado, were published in *Experimental Mechanics, Vol. 28,* No. 2, June, and No. 3, September 1988. The papers in this Special Technical Publication were presented at a symposium held at the Spring 1988 ASTM E24 meeting in Sparks, Nevada, and cover much of the state-of-the-art research being conducted on the behavior of surface flaws.

The papers included in this publication 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 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 behavior of a surface crack is generally limited to predominately elastic stress conditions; considerable research is required for surface cracks under elastic-plastic conditions.

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}, 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 describes the state of the art, as well as identifying the researchers presently pursuing specific topics. The papers are grouped into two sections: Models and Experiments (Monotonic Loading) and Fatigue Crack Growth.

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 give an evaluation of 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 were calculated for a variety of geometries using both nodal force and virtual crack-closure methods. A related configuration was 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, Grant, 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. Near the free surface and for Poisson's ratio near 0.5, the problem becomes more complex.

The next three papers involve aspects of optical stress analysis applied to the surface-crack problem. Smith, Rezvani, and Chang performed photoelastic stress freezing tests of naturally grown through-thickness and surface cracks in bending specimens. Their tests and associated analysis were used to study the difficult problem of free surface effects. As in Blom and Andersson's work, complexities arise, possibly because the photoelastic results were not "sufficiently close to the free surface." The paper by Olinkiewicz, Hareesh, and Chiang combines moiré 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 from 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 investigated dynamic loading of surface-cracked specimens. They compared 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 gave good predictions of surface crack behavior, whereas the critical J for deep through cracks underpredicted the surface crack results.

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

The last two papers of the section on monotonic models and experiments involved 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 types of composites from isotropic K results from the literature. He also compares the results from 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 tensile strength of thick graphite/epoxy laminates using surface crack analysis. Impact damage in this material was represented by a semielliptical surface crack of the same width and depth as the damaged area of broken fibers; the crack plane was nearly perpendicular to the fiber direction. Following a first stage of failure, well predicted by surface crack analysis, a second stage of failure occurred in which damaged layers delaminate from undamaged layers. The second stage failure was predicted using a maximum strain failure criteria.

Fatigue Crack Growth

Over the past decade, the stress-intensity factor concept (ΔK against crack-growth rate) has been shown to correlate quite well with fatigue-crack growth rates for three-dimensional 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 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, 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 three-dimensional variations around the crack front must be considered. Two numerical methods have been 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 have been grouped into four topic areas, stress-intensity factor evaluations during fatigue-crack growth, three-dimensional crack closure and constraint, small-crack behavior, and applications.

Several papers compared crack-growth rates for surface cracks and those of either compact or bend specimens. Carter, Canda, and Blind evaluated several stress-intensity factor solutions for surface cracks and correlated fatigue crack-growth rate data with compact specimen data on an aluminum alloy. For a given stress-intensity factor range, their rates were well within a factor of 2. The slope of their ΔK-rate curve from their surface-crack data, however, was different than the slope from the compact specimen data. The data agreed in magnitude around 12 MPa $m^{1/2}$. Their surface cracks tended to show the presence of a "cusp" where the crack intersected the plate surface. They found, however, that the

Raju-Newman stress-intensity factor equations predicted 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 made a similar conclusion on a fine-grain structural steel. Caspers, Mattheck, and Munz made 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 evaluated the "local average" technique proposed by Cruse and Besuner. Fatigue-crack growth rate measurements made on a Cr-Mo steel compared very well with rates measured on four-point notch bend specimens (rates generally within about 30%).

Jira, Nagy, and Nicholas found that crack-growth rate data measured on surface cracks and on compact specimens correlated well for a titanium alloy using a closure-based ΔK_{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 correlated 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 observed 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 produced the least amount of scatter on a ΔK_{eff}-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 three-dimensional constraint developed around the surface-crack front. Plane-strain conditions around the maximum depth location cause lower opening loads in comparison to the plane-stress regions where the crack intersects the plate surface. A discussion of these constraint variations around the crack front was 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 subsequence crack growth, and to predict the location of fracture initiation around a three-dimensional crack configuration.

Marchand, Dorner, and Ilschner used an advanced ACPD system to study crack initiation and growth under cyclic thermal histories in two superalloys. The initiation of microcracks, 10 to 50 μm in length, could be detected. The specimen used in this study was a double-edge wedge specimen simulating the leading and trailing edges of a gas turbine airfoil. Ramulu studied 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 μm deep) were made at the center of the notch root to act as crack starters. A scanning electron microscope was used to perform fractographic analyses of striation spacings to determine the growth rates for small cracks. The classical "small" crack effect was observed, that is, the small cracks showed 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 conducted tests and analyses on surface cracks in tubular threaded connections, while Niu and Glinka conducted tests and analyses on surface cracks in T-butt welded joints. The experimental and analytical approaches were nearly the same in these papers. An advanced ACPD technique was used to monitor the growth of surface cracks (both depth and length). A weight-function method proposed by Petroski and Achenbach was employed to calculate the stress-intensity factors for surface cracks in these structural configurations. A comparison was made between theoretical and experimentally determined stress-intensity. Experimental stress intensities were determined from measured rates and a ΔK-rate curve for the material of interest. For the butt-weld cracks the theoretical and experimental values compared quite well, but the values for the threaded connection cracks showed some large differences. Several reasons were 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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