Introduction

It is widely understood that small, three-dimensional fatigue cracks can propagate at rates that are considerably faster than those of large cracks subjected to a nominally equivalent stress intensity factor range ΔK. Because many design life predictions are based on data from large-crack specimens, this crack-size effect potentially can lead to nonconservative designs. Thus, the topic of small-crack propagation has become important to the engineering community. There have been a number of recent conferences on this topic [*1–3*] that provide good reviews of the nature and extent of the "small-crack effect."

This Special Technical Publication (STP) is the result of a Symposium sponsored by the Joint ASTM E-9 on Fatigue and E-24 on Fracture Testing Task Group on Small Fatigue Cracks, which was held in San Antonio, TX, in Nov. 1990. The purpose of this STP is to review the state-of-the-art in small-crack test methods and provide the testing community with a single, authoritative reference describing recommended experimental and analytical procedures. Recognizing the unique role of ASTM in developing test standards, each of the authors was invited to provide detailed, quantitative guidance on necessary procedures for testing and data acquisition, including descriptions of the advantages and limitations of the specific technique with sufficient detail to allow use by the inexperienced user. The emphasis in this STP is on characterizing small, three-dimensional fatigue cracks, either naturally or artificially initiated. The potential user is encouraged to consider the specific attributes of the various experimental methods when selecting one or more of the test methods to satisfy his particular research needs. To aid in this process, the following discussion presents an overview of the contents of this monograph.

Fracture Mechanics Parameters for Small Fatigue Cracks—J. C. Newman, Jr.

This paper provides a good introduction to the unique behavior of small fatigue cracks and the primary factors responsible for this uniqueness. A central focus of the author is fracture-mechanics parameters that have been used to correlate or predict the growth of small cracks, with an emphasis on continuum mechanics concepts, crack closure, and non-linear behavior of small cracks. A review of common small-crack test specimens and stress intensity solutions is provided. A major portion of this paper is spent discussing elastic-plastic analysis. The literature in this area is reviewed and simple elastic-plastic and cyclic J-integral estimators are considered for small-crack geometries. The author formulates and applies a simple plastic-zone corrected stress-intensity factor that approximates the J integral surprisingly well. The conclusion is presented that plasticity effects are small for the majority of small-crack data in the literature, and only for situations in which the applied stress was appreciably higher than the flow stress are cyclic plasticity effects significant. The author concludes that crack closure transients are the major factor causing the small-crack effect. These closure transients are attributed to the build up of plasticity-induced crack closure as the crack length increases, and a model is presented for predicting this transient. Finally, using methods described in this paper, accurate predictions of crack shape and sample life are demonstrated for aluminum alloys.

Monitoring Small-Crack Growth by the Replication Method—M. H. Swain

This paper provides a detailed overview of one of the most important, widely used, and least expensive small-crack test methods. The author gives details on preparation of the specimen surface and the replica and discusses replica characterization methods, including many practical tips on use of the technique. The procedure involves creating a series of acetate replicas of the surface of a fatigue specimen throughout its life to produce a permanent record of the state of cracking. The method has been applied to a wide variety of specimen geometries and materials and is applicable to naturally initiated corner and surface cracks. A key attribute of the technique is the ability to track backward in a series of replicas to identify the earliest stages of damage. Replicas may be viewed using either optical microscopy or scanning electron microscopy (SEM). The latter method provides a resolution of approximately 0.1 μm, although the labor and time involved are considerably greater than for optical microscopy. The author discusses stress intensity factor calibrations and presents example small-crack data acquired by replication. A series of practical advantages and limitations of these experimental methods are presented, including effects of hold times and environmental effects. In addition, an appendix is presented, which outlines criteria for selecting cracks that are sufficiently separated as to be considered to have noninteracting stress fields.

Measurement of Small Cracks by Photomicroscopy: Experiments and Analysis–J. M. Larsen, J. R. Jira, and K. S. Ravichandran

The authors discuss a second optically based technique that uses a relatively inexpensive photomicroscope for recording the growth of small fatigue cracks. The experimental apparatus includes a microscope mounted with a 35-mm camera that is triggered by a standard microcomputer, which also controls the testing machine. The paper addresses small-crack issues associated with specimen preparation, effects of surface residual stresses, and characterization of crack shape. The capabilities of the method are documented by data characterizing practical optical resolution, and data are presented to quantify the typical precision of crack length measurements ($\approx$ 1 μm). While this method offers a lower resolution than acetate replication, the semi-automated nature of the approach facilitates the acquisition of a large number of data, which can be analyzed statistically.

The second half of the paper discusses possible pitfalls in the calculation of crack growth rates. A series of analyses is presented of a single, analytically generated, data set to illustrate the influence of the precision of crack length measurement and measurement interval on calculated crack growth rates. It is shown that the ratio of measurement error to measurement interval that typifies many small-crack experiments may have dramatic effects on the calculated crack growth rates over the life of the test. The analysis illustrates the importance of differentiating such effects from any physically inherent variability in small-crack growth rates. To address this problem, a modified incremental polynomial method for calculation of crack growth rates is presented.

The Experimental Mechanics of Microcracks—D. L. Davidson

This paper reviews the extensive accomplishments of the author and his colleagues in applying the scanning electron microscope to the study of small fatigue cracks. The author's pioneering efforts in the development of a high-temperature fatigue loading stage in the SEM are highlighted, and numerous applications of this specialized capability are discussed. The SEM affords high resolution imaging of detailed features of behavior of small cracks, and through the use of stereoimaging, it has been possible to make measurements of a wide range of crack field parameters useful in characterizing the driving force of both small and large cracks. The instrument has provided measurements of displacements and strains in the vicinity of a crack, facilitating documentation of both crack-tip deformation fields and crack closure in the wake of the crack. Probably no other experimental approach has provided such a detailed view of the physical phenomena associated with the propagation of small and large fatigue cracks.

Much of the paper is devoted to highlighting achievements made possible by the SEM observations, including assessments of the factors that appear to be responsible for the differences between the behavior of large and small fatigue cracks. It is concluded from extensive characterization of both small and large cracks using the SEM that the most important factors that differentiate small from large cracks are the crack-size dependence of crack closure and the poor similitude between the crack-tip deformation fields of small versus large cracks. Microstructural effects are also deemed to have a significant influence on small-crack behavior, but changes in crack growth mechanism as a function of crack size have not been observed.

Real-Time Measurement of Small-Crack Opening Behavior Using an Interferometric Strain/Displacement Gage—W. N. Sharpe, Jr., J. R. Jira, and J. M. Larsen

This paper discusses the application of a laser interferometric strain/displacement gage (ISDG) to the study of small fatigue cracks. The technique, which is applicable to both naturally and artificially initiated cracks, is essentially a noncontacting, short-gage-length extensometer having a displacement resolution of approximately 5 nm. From data of applied load versus crack-mouth-opening displacement, measurements of crack-opening compliance and observations of crack closure are obtained. Computerization makes real-time analysis of the data possible and efficiently handles the large quantity of data that is acquired. The general principles of operation of the ISDG are discussed, and four variations of the instrument currently in use are reviewed. The authors offer a number of practical considerations for application of this approach to small-crack testing and present example data illustrating the capabilities of the method for measurement of crack closure and crack length. When combined with independent measurements of surface crack length, the compliance measurements provided by the ISDG may be used to calculate instantaneous crack shape. Because the data are available in real time, the ISDG may be used for feedback control of fatigue tests following procedures similar to those used for automated testing of conventional large-crack specimen (for example, $\Delta K_{decreasing}$, ΔK_{th} tests).

Direct Current Electrical Potential Measurement of the Growth of Small Fatigue Cracks—R. P. Gangloff, D. C. Slavik, R. S. Piascik, and R. H. Van Stone

This paper provides an extensive and detailed review of direct current electric potential techniques for characterizing small fatigue cracks. Using the descriptions provided of the required apparatus and experimental arrangements, any good experimentalist should be able to duplicate and apply this technique. In particular, there is an excellent description of experimental issues such as probe location, the effect of changes in probe location, thermal electromotive force effects, and methods for dealing with crack shorting effects. Materials covered include ferrous, aluminum, titantium, and nickel alloys. The authors conclude that, in these metallic materials, electric potential techniques can be used to monitor cracks greater than 75 μm and resolve crack length changes of 1 to 5 μm. A review of models for predicting the dimensions of three-dimensional cracks from changes in measured electric potential is provided. For accurately predicting crack length, assumptions regarding crack shape must be made, however, the authors provide evidence that, in general, crack shape is well-controlled and can be predicted. For materials in which crack shape has not been previously characterized, methods are suggested for verifying the required assumptions. The paper contains many examples of applications of the electric potential technique to small-crack characterization, with special emphasis on novel applications in investigations involving environmental and elevated temperature effects. The authors include examples demonstrating how this technique can be used in sophisticated ways to develop an understanding of the mechanisms controlling small-crack propagation.

An Ultrasonic Method for Measurement of Size and Opening Behavior of Small Fatigue Cracks—M. T. Resch and D. V. Nelson

In the past 25 years ultrasonic techniques have only occasionally been used to monitor fatigue cracks. In this paper, the authors provide a case for more wide spread use of the surface acoustic wave (SAW) technique and give tips on how to effectively apply it. A detailed and thorough review is given of SAW techniques for use in detecting and measuring small fatigue cracks. Models are described for predicting a normalized crack depth from amplitude of the reflected signal, however, similar to electric potential techniques, relating this value to the actual crack depth and length dimensions requires either a knowledge of the crack surface length or assumptions about the crack aspect ratio. Fortunately, for many materials and specimen designs, such assumptions can be readily made and have been verified. Experimental details such as optimizing operating frequency and coupling wedge design are described. Cracks as small as 50 μm can be measured and, using special signal processing techniques (split spectrum processing), cracks as small 20 μm have been detected. The authors point out that a maximum measureable crack size limitation of 150 to 250 μm exists. This limit can, however, be altered by appropriate changes in transducer design and operating frequency. The use of the SAW method for measuring crack opening behavior of small cracks is also reviewed along with recent findings. The SAW technique is shown to be quite sensitive to crack opening and can detect both the initial opening of a crack and the point at which the crack is fully opened. These results are compared to those obtained using SEM (compliance) techniques, and the authors conclude that the SAW method gives information that complements compliance techniques and thus provides a more complete picture of closure. They show that crack-opening behavior as determined by both techniques is sensitive to surface residual stresses.

Simulation of Short Crack and Other Low Closure Loading Conditions Utilizing Constant-K_{max} ΔK-Decreasing Fatigue Crack Growth Procedures—R. W. Hertzberg, W. A. Herman, T. Clark, and R. Jaccard

As an alternative to small-crack testing, the authors present an argument for a large-crack approach that obviates many of the difficulties associated with small-crack testing. This approach employs conventional large-crack specimens tested under constant-K_{max}, ΔK-decreasing conditions. The key presumption of this approach is that the rapid growth of small cracks is the result of differences in crack closure for small versus large cracks. Thus, conventional large-crack data, which typically exhibit fully developed levels of crack closure, particularly in the near-ΔK_{th} regime, are assumed to be nonconservative relative to the data of small cracks which, due to their size, may not have fully developed crack closure. During a constant-K_{max} test, as ΔK decreases, K_{min} eventually exceeds the stress intensity factor for crack closure, resulting in closure-free crack growth rates. The resulting data are useful for estimating maximum crack growth rates that may result under a variety of "low-closure" conditions. Potential applications include effects of high tensile residual stresses produced by welding and effects of compressive loads under negative R or variable amplitude fatigue. The paper provides guidelines for conducting constant-K_{max}, ΔK-decreasing tests, and data from a number of materials are presented to demonstrate the capabilities of this approach for estimating an upper bound for small-crack growth rates. This approach cannot be expected to address small-crack effects associated with factors other than crack closure, such as test conditions that violate the applicability of the linear elastic parameter ΔK or effects of microstructural variables.

References

[1] *Small Fatigue Cracks*, R. O. Ritchie and J. Lankford, Eds., The Metallurgical Society, Inc., Warrendale, PA, 1986.

[2] *The Behaviour of Short Fatigue Cracks*, EGF Publication 1, K. J. Miller and E. R. de los Rios, Eds., Mechanical Engineering Publications Ltd., London, 1986.

[3] *Short-Crack Growth Behaviour in Various Aircraft Materials*, AGARD Report 767, P. R. Edwards and J. C. Newman, Jr., Eds., NATO Advisory Group for Aerospace Research and Development, 1990.

James M. Larsen
Wright Laboratory, Materials Directorate,
Wright-Patterson Air Force Base, OH 45433;
symposium cochairman and coeditor.

John E. Allison
Ford Scientific Laboratory,
P.O. Box 2053
Dearborn, MI 48121;
symposium cochairman and coeditor.