Mixed-Mode Crack Behavior

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EDITORS

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Foreword

The Symposium on Mixed-Mode Crack Behavior was held 6–7 May 1998 in Atlanta, GA. The symposium was sponsored by ASTM Committee E8 on Fatigue and Fracture and its Subcommittee E08.01 on Research and Education.

The symposium was chaired by Keith J. Miller, of the University of Sheffield, and David L. McDowell, of the Georgia Institute of Technology. These men also served as editors for this resulting publication.

Contents

Overview

Engineering components and structures necessarily involve the introduction of defects, including holes, grooves, welds, and joints. The materials from which they are made have smaller imperfections, such as surface scratches, inclusions, precipitates, and grain boundaries. All of these defects range in size from sub-microns to many millimeters. Engineers who design such components or structures must be fully cognizant of the level and orientation of the applied loading (whether static or dynamic, of constant or variable amplitude, or proportional or nonproportional) and the density, size, shape, and orientation of the defects. Under combined loading, or even remote Mode I loading, effective strain or strain energy density approaches can lead to dangerously nonconservative predictions of fatigue life, and similarly the opening mode stress-intensity factor, K_I, is seldom appropriate for describing local mixed-mode crack growth.

For mixed-mode conditions, the crack growth direction does not follow a universal trajectory along a path in the orthogonal mixed-mode K_I-K_{II}-K_{III} space. Under cyclic loading, a surface in this space can be defined as representing an envelope of constant crack growth rate that tends towards zero for the threshold state. In general, this envelope depends intimately on the crack driving and resisting forces. The application of linear elastic fracture mechanics (LEFM), elastic-plastic fracture mechanics (EPFM), or microstructural fracture mechanics (MFM) is dictated by the scale of plasticity or material heterogeneity relative to the crack length, component dimension, and damage process zone. All of these features come into play during mixed-mode loading and mixed-mode crack growth.

ASTM special technical publications (STPs) have a rich history of considering complex aspects of fracture such as effects of mixed-mode loading. This subject has been couched under various labels such as multiaxial fatigue, 3-D crack growth, and microstructurally sensitive crack growth, among others. From previous symposia and related STPs, we have gained understanding of the physics of these phenomena and have developed appropriate experimental techniques, yet our understanding is far from complete. There is still a struggle to identify the role of material resistance in establishing the growth path for the mixed-mode propagation of cracks. Consequently, industrial practice, codes, and standards have not been updated in the face of this uncertainty.

The ASTM E08-sponsored Symposium on Mixed-Mode Crack Behavior was held in Atlanta, GA on May 6–7, 1998, and gave rise to this STP. The conference was international and balanced in scope, as witnessed by the presentation of over 20 papers addressing the following topics:

- Elastic-Plastic Fracture
- Three-Dimensional Cracks
- Anisotropic Fracture and Applications
- Fracture of Composite Materials
- Mixed-Mode Fracture Toughness
- Mixed-Mode Fatigue Crack Growth
- Experimental Studies in Mixed-Mode Fatigue and Fracture

In practice, cracks that are confined to follow weak paths of material resistance along weld fusion lines or relatively weak material orientations due to process history, composite reinforcement, or interfaces will often be subject to local mixed-mode crack driving forces. One of the more difficult challenges facing treatment of mixed-mode effects is the difference between global (apparent) mode-mixity and local (crack tip) mode-mixity due to microstructure heterogeneity, for example, at the tip of small fatigue cracks or within damage process zones at the tips of longer cracks. Although a number of technologies have already benefitted from an enhanced understanding of mixed-mode fatigue and fracture, much design today is performed assuming local Mode I conditions even when this assumption is not applicable. Briefly stated, too much focus is placed on the crack driving force and too little on micromechanisms of damage that lead to crack advance.

This STP is intended to contribute to a deeper understanding of these issues. Among the authors of this volume are some of the leaders in the disparate and far-reaching field of mixed-mode fracture. Consequently the papers contained herein span the range of experimental, computational/theoretical, and physical approaches to advance our understanding of the various aspects of mixed-mode fracture problems, and are organized into several categories. The first set of papers deals with experimental observations and modeling of crack extension in ductile metals under mixed-mode loading conditions. The paper by Laukkanen and colleagues is selected to lead off this STP because it offers a fairly comprehensive evaluation of the effects of mixed Mode I-II loading on elastic-plastic fracture of metals and provides experimental data for a range of alloys as well as taking an in-depth look at failure mechanisms ahead of the crack. This paper was recognized as the outstanding presentation at the symposium. The paper by Dalle Donne approaches the same class of problems using the crack tip opening displacement approach. Ma and colleagues apply computational methods to predict the crack growth path for mixed Mode I-II behavior of 2024-T3 Al. Chao and Zhu develop an engineering approach to problems of mixed-mode growth to consider experimental observations of crack path in terms of a plastic fracture criterion based on crack tip fields. Lam et al. employ the T^* integral to model crack growth by computational means along curved paths. Hiese and Kalthoff present a study that considers the determination of valid mode II fracture toughness, an essential parameter in any practical mixed-mode law. The work of Deng et al. suggests that a critical level of the generalized crack tip opening displacement (CTOD) at a fixed distance behind the crack tip dictates the onset of crack extension, while the direction of the crack path is determined by maximizing either the opening or shearing component of the CTOD. Since the crack path is a prior unknown in complex components, computational fracture approaches must be flexible and adaptive, permitting re-meshing to account for the evolution of the crack; James and Swenson discuss recent developments in two-dimensional modeling of mixed Mode I-II elastic-plastic crack growth using boundary element and re-meshing techniques.

The next set of papers considers the growth of cracks in materials with a strongly defined mesostructure that controls mixed-mode fracture. Kishimoto and colleagues provide a detailed experimental study of the mixed-mode fracture behavior of silica particulate-filled epoxide resin that is used in electronic packaging applications. The driving force for cracks between layers of material in composites or lying within bimaterial interfaces between anisotropic materials is of fundamental importance to fracture analysis; in this volume Xue and Qu present the first analytical solution ever obtained for the mixed-mode stress intensity factors and crack opening displacement fields for an arbitrary elliptical interface crack between two distinct, anisotropic, linear-elastic half spaces. In an experimental study employing computed microtomography to quantify closure of deflected fatigue cracks in highly anisotropic Al-Li 2090, Stock presents a means to study highly complex crack opening and sliding fields in anisotropic materials having, in this case, mesostructure and mesotexture. Zhai and Zhou employ a novel local mixed-mode interface separation law for all interfaces (and elements) within a finite element mesh to predict crack paths in ceramic composites under dynamic loading conditions as a function of interface strength and phase properties; this approach is not of the classical singularity type, but rather can be categorized as a cohesive zone approach.

The final set of papers deals primarily with various aspects of fatigue crack growth under mixed-mode loading conditions. Bennett and McDowell conduct computational studies using two-dimensional crystal plasticity to shed light on the influence of intergranular interactions on driving forces for the formation and early growth of fatigue cracks in polycrystals, as well as discrete orientation effects of neighboring grains and free surface influences on the crack tip displacements for microstructurally small surface cracks in polycrystals. The paper by Miller and colleagues raises a number of stimulating issues for further consideration, it also highlights the classification of crack growth behavior as belonging principally to either normal stress- or shear stress-dominated categories. Ashbaugh et al. report on a detailed fractographic study of crack growth behavior under variable amplitude, mixed-mode loading conditions. Shlyannikov provides experimental data regarding mixed crack growth in center cracked and compact tension shear specimens. Tanaka and associates report on their axial-torsional studies of propagating and nonpropagating fatigue cracks in notched steel bars, with emphasis on the dependence of the fatigue limit on notch root radius and mixity of applied loading. John and colleagues consider the fatigue threshold for a single crystal Ni-Base superalloy under mixed-mode loading, a problem of great relevance to fatigue limits in the design of gas turbine engine components, for example.

One of the important points of convergence of this Symposium was the realization that, for a large number of mixed-mode crack growth problems of which we are aware, there are two fundamentally distinct classes of growth: maximum principal stress-dominated and shear-dominated. This is true regardless of whether we consider static or cyclic loading conditions. This observation is likely to enable the development of certain very robust, simplified, material-dependent design approaches for cracks in components and structures. Another point, emphasized in several papers, is the intimate connection of the crack tip displacement concept to mixed-mode elastic-plastic fracture and fatigue processes.

As coeditors of this publication, we are greatly indebted to the host of international reviewers who are essential when bringing a publication of this nature to press. We can claim that this volume follows in the proud tradition of the thorough peer-review system that is characteristic of ASTM STPs in fracture and fatigue. We trust that this STP will give valuable insight into various aspects of mixed-mode fracture, as well as provide substantial inroads to resolving some characteristic, yet fundamental mixed-mode behavioral problems frequently observed in engineering materials, components, and structures.

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