# Overview

The effect of the multiaxial stress state on cyclic deformation and fatigue life has emerged over the last two decades as one of the most rapidly developing areas of fatigue research. The intense focus on this subject may be attributed to the general recognition of its importance in the fatigue design of components as well as the relatively recent widespread availability of high-quality multiaxial testing equipment. Marked advances in understanding the influence of both material structure and multiaxiality of loading have been made in the past two decades. This is the second symposium of its type sponsored by ASTM since 1980. The first, the Symposium on Multiaxial Fatigue, was held in San Francisco 15–17 Dec. 1982, with a resulting ASTM special technical publication *(Multiaxial Fatigue, ASTM STP 853).* The results of the more recent Symposium on Multiaxial Fatigue, held in San Diego 14–15 Nov. 1991, forms the basis for this special technical publication.

This symposium was conceived and planned within ASTM Subcommittee E09.01 on Fatigue Research, a subcommittee of ASTM Committee E09 on Fatigue. The purpose of the symposium was to communicate the most recent international advances in multiaxial cyclic deformation and fatigue research as well as applications to component analysis and design. Reflective of the continuing yet incomplete development of the subject, this volume will be of considerable interest to researchers and industrial practitioners of fatigue design. The papers herein predominately reflect a concern with stress state effects on cyclic deformation and fatigue of a wide range of monolithic metals, with applications ranging from power plant pressure vessel components to hot section jet engine components to automotive assemblies. The understanding of multiaxial loading effects on fatigue life has proven to be a very challenging and somewhat elusive pursuit; this volume provides insight into some important advances of our understanding during the last ten years.

The collection of 24 papers published in this volume has been grouped into five categories. Each category reflects the most fundamental area of contribution of its papers, although a certain degree of overlap is unavoidable. These categories are multiaxial fatigue life models, experimental multiaxial fatigue studies, multiaxial stress-strain behavior, multiaxial micro/macro crack growth studies, and multiaxial fatigue of notched components.

## Multiaxial Fatigue Life Models

Prior to the 1960s, most multiaxial fatigue life prediction schemes concentrated on high-cycle fatigue applications. Effective stress, maximum shear stress, or modified schemes involving tensile mean stress and/or hydrostatic stress were most applicable in the HCF regime. With increasing concern for low-cycle fatigue applications following the 1960s, multiaxial fatigue approaches adopted strain-based methodologies. The decade of the 1970s witnessed the introduction of so-called critical plane approaches which made connections between fatigue crack initiation on specific planes at the surface of the material and the maximum shear strain range and/or normal strains on these planes. The first paper in this volume reviews these approaches and offers significant experimental insight into the relative role of microcrack nucleation and propagation in multiaxial fatigue. Extensive data sets including microcrack sizes and shapes



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over a wide range of stress states are considered. The key conclusions are (1) each material has a potentially distinct mode of resistance to fatigue crack initiation, and (2) the critical plane model selected should always reflect the actual physics of microcracking, either shear-based or normal stress/strain-based. The second paper provides an application of these critical plane principles to constant and variable amplitude fatigue of SAE notched shaft specimens; a novel computational scheme for multi-surface plasticity theory is used to predict the stress-strain histories which are essential for fatigue life analyses. The third and fourth papers in this section deal with promising hysteretic energy-based approaches with provision for mean stress effects. The fifth paper employs a triaxiality factor to correlate fatigue data over a range of stress states.

The final two papers in this section employ incremental damage approaches to the multiaxial fatigue problem, permitting consideration of quite arbitrary loading histories. The first of these two papers uses a thermoviscoplasticity theory to determine incremental inelastic strains; then creep and fatigue damage increments are determined and summed to assess total damage. The last paper considers the prediction of the high-cycle fatigue response using micromechanical techniques and a shakedown approach to assess the possibility of persistent cyclic plastic strains.

### Experimental Multiaxial Fatigue Studies

Much of our collective knowledge regarding multiaxial fatigue has developed by virtue of experimental studies of various materials. In this section, the papers consider, among other things, effects of complex loading and material anisotropy. The first paper presents a high-temperature tension-torsion experimental study of the in-phase and out-of-phase fatigue behavior of a superalloy. Several fatigue theories are examined in terms of their correlative capability.

In the second paper, the effects of anisotropy of initially cold-worked Al-6061-T6 on tension-torsion fatigue behavior are studied and correlated using an anisotropic generalization of a critical plane theory. The third papers reports results of high-temperature fatigue tests consisting of sequences of uniaxial and torsional loading of tubular specimens; strongly nonlinear interaction effects are observed for tension-torsion loading and are attributed to oxide-induced cracking and differences of microcrack initiation and growth between uniaxial and torsional cyclic loading. The last paper presents a unique, relatively low-cost test method which may achieve a wide range of biaxiality ratios using only uniaxial testing equipment.

Continued experimental examination of microcracking and effects of complex multiaxial loading paths, as reported in this section, will prove to be an essential tool in further advancing our understanding of the fatigue process.

### Multiaxial Stress-Strain Behavior

It is increasingly evident that any successful multiaxial fatigue life prediction methodology invariably relies on accurate multiaxial cyclic stress-strain relations for input. In turn, development of constitutive equations for cyclic inelastic material behavior depend on carefully conducted combined stress state experiments. The first two papers in this section deal with such experimental studies on advanced metallic alloys. The first paper considers the appropriateness of using a $J_2$-based constitutive model to correlate both uniaxial and pure torsional thermomechanical test results. The second paper reports the behavior of a single crystal superalloy under tension-torsion loading of thin-walled tubular specimens.

The next two papers in this section study the performance of cyclic inelasticity theories. In the third paper, the concept of an irreversible component of cyclic inelastic strain is introduced to model the path-dependent cyclic hardening behavior of an austenitic stainless steel. The fourth paper examines the predictive capability of two rate-independent multisurface plasticity models for nonproportional loading paths and introduces a modified integration scheme for near neutral loading conditions.

The final paper in this section addresses the problem of predicting cycle-dependent plastic strain accumulation for nonproportional loading paths typical of pressure vessel and piping components with steady primary stresses and alternating secondary stresses. Using a multisurface plasticity theory, the author introduces a ratchet assessment diagram as a graphical presentation of results and discusses these results in terms of ASME code considerations.

### Multiaxial Micro/Macro Crack Growth Studies

There has been a growing emphasis during the 1980s on applying fracture mechanics principles to fatigue, including growth of very short cracks which have conventionally fit within the so-called "fatigue crack initiation" regime. Numerous recent studies have considered the details of crack growth for microstructurally short cracks and the transition to long crack behavior. The first two papers in this section examine experimentally the propagation behavior of microcracks in low-cycle fatigue under tension-torsion loading of thin-walled tubular specimens. Results are correlated using critical plane concepts as a basis for microcrack propagation laws.

The last two papers in this section consider macrocrack propagation under mixed mode conditions in a biaxial stress field. The third paper examines self-similar crack propagation as a function of mode mixity for a high-strength steel; several mixed mode theories are unsuccessful at correlating mixed mode results based on constants determined using Mode I data. The final paper deals with curvature of the growth of initially longitudinal cracks in thin pressurized and independently axially loaded cylinders.

### Multiaxial Fatigue of Notched Components

The preceding sections of this volume present much of the latest research regarding multiaxial cyclic deformation and fatigue. Ultimately, the application of these concepts to life prediction of notched structural components is the primary driving force for this research. In this section, four papers are included which represent a variety of applications.

The first paper presents a method of estimating the local cyclic strains given the autofrettage history of pressurized components and compares the results with finite element analyses. The second paper presents a method to estimate notch root stresses and inelastic strains, including plastic and creep strains, based on two linear finite element analyses per point on the load versus notch root strain curve.

The third paper compares the ASME Boiler and Pressure Vessel Code multiaxial low-cycle fatigue approach with a local stain approach and the Japanese MITI Code, including a study of a pressure vessel component. The final paper in this section presents a methodology for correlating the fatigue life of composite hip prothesis components with the progressive degradation of stiffness.

The papers briefly outlined in this overview should provide a glimpse into the advances made in the subject of multiaxial fatigue from the 1982 ASTM symposium to the present. We should also acknowledge the very dynamic and important activities and symposia elsewhere on this subject which have contributed so greatly to this volume and the state of the art in multiaxial fatigue. The editors of this volume gratefully acknowledge the extremely dedicated efforts of the authors, reviewers, and ASTM personnel who have made this publication possible.

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