Overview

The importance of fatigue and deformation of materials under multiaxial loads has gained significant recognition over the last quarter century. The advances in sophisticated materials testing equipment and digital computer systems have enabled many researchers to explore a multitude of testing techniques to assess the behavior of materials and structural components. The result has been the evolution of several testing procedures and generation of indispensable multiaxial fatigue and deformation data on different types of materials. Theoretical models have been developed to estimate the deformation behavior and fatigue lives of materials under multiaxial loading conditions. Numerous conferences and symposia have been sponsored by various societies to document the technical achievements in the field. Two such ASTM sponsored symposia have resulted in the following valuable special technical publications: (1) *Multiaxial Fatigue (ASTM STP 853)* and (2) *Advances in Multiaxial Fatigue (ASTM STP 1191).* This special technical publication is the result of a third ASTM sponsored symposium on Multiaxial Fatigue and Deformation Testing Techniques, which was held on 15 May 1995 in Denver, Colorado.

The symposium on Multiaxial Fatigue and Deformation Testing Techniques was sponsored by the ASTM Committee E8 on Fatigue and Fracture and its Subcommittee E08.05 on Cyclic Deformation and Fatigue Crack Formation. The symposium's focus was on state-of-the-art testing techniques for characterizing the multiaxial fatigue and deformation behaviors of monolithic and composite materials. The main purpose of the symposium was to facilitate the development of standardized procedures for testing structural materials under multiaxial loading conditions.

This volume contains a set of fourteen papers, which were presented at the Symposium on Multiaxial Fatigue and Deformation Testing Techniques. These papers deal with both experimental and theoretical aspects of the multiaxial fatigue and deformation behaviors of structural materials. The papers are separated into the following categories: (1) Multiaxial Testing Facilities, (2) Multiaxial Deformation, (3) Multiaxial Fatigue, and (4) Structural Failure and Crack Propagation Under Multiaxial Loading. These four broad categories are intended to provide an orderly grouping of the presented papers.

Multiaxial Testing Facilities

Multiaxial testing is performed typically on tubular or cruciform specimens. The tubular specimens are employed for axial, torsional, internal pressure, external pressure, or combinations of these types of loads, whereas the cruciform specimens are used for biaxial tensile or compressive loads. The first paper in this category deals with the development of a multiaxial testing facility that is suitable for tubular specimens. The capability of this facility is demonstrated by testing composite specimens manufactured from glass-fiber reinforced epoxy tubes. The second paper describes a test facility that is designed to perform in-plane biaxial tests on cruciform specimens and on structural elements of advanced materials. Different features of the test facility include a digital controller and associated software to control four hydraulic actuators, a quartz lamp radiant furnace, an environmental chamber, and an in situ crack monitoring system. The third paper in this category illustrates the design and performance of a coil fixture for inductively heating cylindrical specimens during mechanical testing. This novel approach subdivides the induction coil into three individually adjustable segments. It is shown that temperature variation in the gage section of a large tubular specimen can be controlled to within 1% of the nominal test temperature with the adjustable induction coil fixture.

Multiaxial Deformation

Deformation of materials under monotonic and cyclic multiaxial loads has been the subject of many investigations in the last two to three decades. In particular, the shapes of the multiaxial load paths (proportional versus nonproportional) have been shown to have a significant influence on the hardening behavior of materials. Each of the four papers in this category addresses a different aspect of the multiaxial deformation behavior of materials. In the first paper, a succinct review of the research under large strain conditions is presented and the effects of large compressive and torsional prestrains on the subsequent large strain deformation behavior of 304L stainless steel are experimentally evaluated. In addition, experimental results depicting the influence of a large torsional prestrain on the subsequent small strain biaxial deformation behavior of the 304L stainless steel are illustrated, and issues for modeling the small strain deformation data are discussed. The second paper describes procedures for experimentally determining the room temperature yield and high temperature flow surfaces of 316 stainless steel under axial-torsional loading with a commercially available high temperature extensometer. An inelastic strain offset criterion is used to determine the yield surfaces, whereas a constant inelastic strain rate criterion is employed to establish the flow surfaces. The third paper addresses the influence of the loading path shape on the cyclic axial-torsional hardening behavior of 316 stainless steel. In this experimental investigation authors identify nonproportional loading paths that lead to higher levels of hardening than the conventional 90° out-of-phase axial-torsional loading. The final paper proposes two analytical models based on strain energy density to estimate the stresses and strains at the root of a notch under multiaxial nonproportional loading. In order to validate the models, results generated from the models are compared with stress-strain data obtained from finite element analyses.

Multiaxial Fatigue

Fatigue under multiaxial loads has been the topic of many investigations with emphasis both on experimental and theoretical aspects. Predicting the multiaxial fatigue crack initiation life requires complete knowledge of the cyclic stresses and strains and life prediction models that are appropriate for the damage mechanisms exhibited by the particular material under consideration. In this category, the first paper reports experimental results from a biaxial fatigue crack initiation study on cruciform specimens manufactured from an aluminum alloy. Fatigue lives under proportional and nonproportional loading histories are estimated with two incremental plastic work based fatigue life prediction approaches, which account for the influence of mean stresses. The second paper describes, in detail, a testing technique for performing strain-controlled, thermomechanical fatigue tests on thin-walled tubular specimens under combined axial-torsional loading conditions. Four types of axial-torsional, thermomechanical fatigue tests are described, and experimental results generated on a cobalt-base superalloy, Haynes 188, are discussed. The third paper deals with fretting fatigue of machine elements subjected to combined axial and transverse loading. Experimental results from fretting fatigue tests on normalized steel specimens are presented, and fracture mechanics is used to estimate fretting fatigue limits. The final paper in this category describes a technique for conducting monotonic and cyclic tests under uniaxial and biaxial loads on ceramic matrix composite tubes. Uniaxial and biaxial fatigue behaviors of a ceramic matrix composite and damage and failure modes exhibited by the composite under the investigated loading conditions are discussed.

Structural Failure and Crack Propagation Under Multiaxial Loading

The final category in this book contains three papers on the topics of structural failure and crack growth under multiaxial loading conditions. The first paper deals with crack growth under mixed Mode I and Mode II conditions in cruciform specimens made from an aluminum alloy and a structural steel. Crack resistance curves under mixed mode conditions, presented in terms of the magnitude of a crack tip displacement vector, are compared to the conventional R-curves obtained with compact-tension and center-cracked specimens. The second paper presents results from an experimental and analytical study on the structural failure of corrugated board cylinders. Failure data generated in experiments under compressive and torsional loads are compared to the failure envelope obtained with finite element analysis and Tsai-Wu criterion. In the third paper, experimental results obtained in a crack growth study on cruciform specimens made from a titanium alloy are reported. Block loading histories consisting of major and minor cycles are imposed on the cruciform specimens containing crack initiator sites prepared with electric spark discharge. The crack growth rates observed under different block loading histories are compared.

The experimental techniques presented in this book show some of the significant improvements that have occurred in the field of multiaxial testing during the past five to ten years. It is our sincere hope that the papers contained in this book will shed some light on multiaxial testing techniques and that this book will serve as a valuable technical resource. We would like to thank the authors and reviewers without whose contributions and meticulous efforts this book would not have been possible. We are grateful to the ASTM staff (Ms. Dorothy Savini, Hannah Sparks, Shannon Wainwright, Monica Siperko, Kathy Dernoga, and Helen Hoersch) for their professional assistance, cooperation, and patience.

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