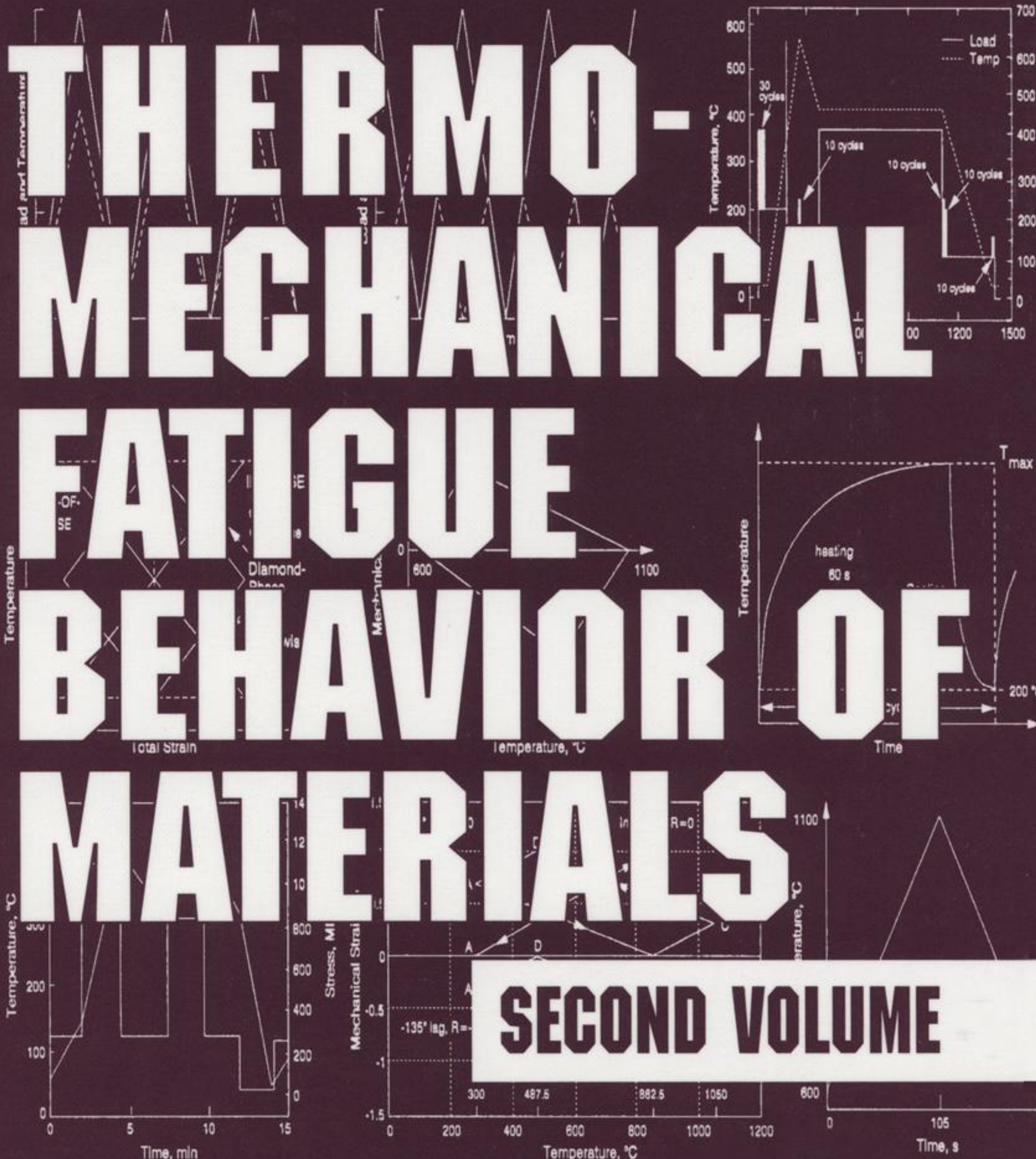
THERMO-MECHANICAL FATIGUE BEHAVIOR OF MATERIALS



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Michael J. Verrilli and Michael G. Castelli, Editors

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Foreword

This publication, *Thermomechanical Fatigue Behavior of Materials: Second Volume,* contains papers presented at the Second Symposium on Thermomechanical Fatigue Behavior of Materials held 14–15 November 1994 in Phoenix, AZ. The symposium was sponsored by ASTM Committee E-8 on Fatigue and Fracture. Michael J. Verrilli, of the NASA Lewis Research Center in Cleveland, and Michael G. Castelli, with NYMA, Inc., NASA LeRC Group in Brook Park, OH, presided as symposium chairmen and are editors of the resulting publication.

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Overview

Background

Virtually all high-temperature components experience service cycles that include simultaneous temperature and load cycling, or thermomechanical fatigue (TMF). Materials testing and characterization are required to capture the often unique synergistic effects of combined thermal and mechanical loading. This information can make possible the proper formulation of models used for component lifetime prediction and design, and can guide materials development.

The paper included in this volume were written in conjunction with a symposium organized to disseminate current research in the area of TMF behavior of materials. ASTM, through the members of Committee E-8 on Fatigue and Fracture, has traditionally had a keen interest in thermal and thermomechanical fatigue, as evidenced by the numerous STPs which discuss the issue. In 1968, the first ASTM paper on TMF appeared in STP 459, *Fatigue at High Temperature.* Carden and Slade discussed the behavior of Hastelloy X under strain-controlled isothermal and TMF conditions. *The Handbook of Fatigue Testing* (STP 566, published in 1974) described a technique for thermal fatigue testing of coupon specimens as well as the structural TMF test system for the airframe of the Concorde. STP 612, *Thermal Fatigue of Materials and Components* (1975) is the proceedings of the first comprehensive ASTM symposium on thermal and thermomechanical fatigue. Paper topics included TMF test techniques, life prediction methods, and TMF behavior of advanced materials such as ceramics and directionally-solidifed superalloys. A symposium entitled "Low Cycle Fatigue" (STP 942) held in 1988 contained five papers on thermal and thermomechanical fatigue. TMF test technqiues, deformation behavior and modeling, and observation of microstructural damage were presented. The first ASTM STP devoted to TMF of materials (and the predecessor to this volume) was the proceedings of the 1991 symposium on *TMF Behavior of Materials* (STP 1186). Several papers discussed the role of environmental attack on performance and life modeling of high-temperature alloys subjected to TMF loadings. In addition, this STP contains two papers which discuss TMF of metal matrix composites, an indication of the emerging interest in this class of materials for high-temperature applications.

ASTM is also actively pursuing development of a standard practice for TMF testing. Numerous standard practices for isothermal low-cycle fatigue testing exist (including ASTM E606 for strain-controlled testing and E466 for load-controlled testing), but none exist for TMF. However, the first standard for strain-controlled TMF testing of metallic materials is under development by an ISO working group in conjunction with ASTM Committee E-8 on Fatigue and Fracture. We expect that the resulting international standard will be the foundation of an ASTM standard.

Summary of the Papers

High-Temperature Structural Alloys

Most papers in this section discuss high-temperature alloys used for gas turbine engines, such as Ni-base superalloys and titanium alloys. Steels which are subjected to TMF conditions in power generation applications are discussed as well. The topics of the papers in this section on TMF behavior of high-temperature alloys include crack initiation and growth, novel experimental techniques, deformation modeling, and the role of coatings on life and microcracking.

Chataigner and Remy studied the TMF behavior of a chromium-aluminum coated [001] single crystal using a diamond-shaped strain-temperature cycle. They found no difference between the lives of coated and bare specimens. A life prediction model based on microcrack propagation due to fatigue and oxidation damage is evaluated.

Kraft and Mughrabi examined the crack evolution and microstructural changes of a single-crystal superalloy subjected to in-phase, out-of-phase, and diamond TMF cycle types. The morphology of the γ' structure after TMF cycling was found to be dependent on cycle type. The maximum tensile stress response of the [001] oriented specimens governed life for all the cycle types.

Meyer-Olbersleben et al. performed thermal fatigue (TF) experiments on blade-shaped, wedge specimens made of single-crystal superalloys. They proposed an "integrated" approach where the temperature-strain history measured during TF experiments is used as the basic cycle for a TMF investigation. This method is suggested as an alternative to finite element calculations to deduce the stress history of wedge specimens.

Bressers, Martínez-Esnaola, Timm, and co-workers contributed three papers examining the role of a coating on the TMF behavior of single-crystal Ni-base superalloys. In the first contribution, Bressers et al. studied the effect of TMF cycle type on the lives of a coated and uncoated single-crystal superalloy. This study reports the various modes of crack initiation, crack growth, and the stress and inelastic strain response due to in-phase cycle and $-135°$ lag cycle. For uncoated specimens, the cycle type significantly affected the mode of crack initiation. Also, life debits due to the presence of the coating varied as a function of strain range and cycle type. In the second paper by this group, Martínez-Esnaola et al. investigated cracking of the coating on the Ni-base single crystals subjected to the $-135°$ lag TMF cycle. The mode of coating crack initiation depended on the applied mechanical strain range, while crack initiation of bare specimens occurred via a single mode. A fracture mechanics model was applied to examine the effects of parameters such as coating thickness and temperature on the coating toughness, strain to cracking, and crack density. In the third contribution, Bressers et al. used a crack shielding model in an effort to explain the experimentally-observed debit in TMF life due to the presence of the coating on the single-crystal specimens. Higher crack-growth rates of the main crack were observed in coated specimens relative to the uncoated material. The crack shielding model was used in a parametric study to stimulate the growth of interacting, parallel cracks. The results of the analysis indicated that crack shielding effects due to the presence of the coating did not play a primary role in the life difference, and that other factors should be investigated as the potential cause, such as presence of residual stresses or thermal expansion mismatch of the coating and substrate.

Two papers discussed TMF of stainless steels. Zamrick and his co-workers compared the TMF and high-temperature LCF behavior of type 316 stainless steel. Yamauchi et al. conducted structural thermal fatigue tests on tubes of 304 stainless steel to simulate the service conditions. A FEM stress analysis revealed the stress state and temperature-strain phasing for the inner and outer surfaces of the pipe which experienced through-thickness gradients during the tests. The analysis, combined with uniaxial specimen tests, explained the experimentally-observed difference of crack initiation life between the inner and outer surfaces.

Arnold et al. present their recent developments in viscoplastic deformation modeling. The model utilizes an evolutionary law that has nonlinear kinematic hardening and both thermal and strain-induced recovery mechanisms. One tensorial internal state variable is employed. A unique aspect of the present model is the inclusion of nonlinear hardening in the evoluation law for the back stress. Verification of the proposed model is shown using non-standard isothermal and thermomechanical deformation tests on a titanium alloy commonly used as the matrix in SiC fiber-reinforced composites.

A novel test method to assess the role of temperature in determining the operative fracture mode and crack growth rates in superalloy single crystals is presented in the paper by Cunningham and DeLuca. The technique involves varying temperature with crack length according to a user-supplied function and was shown to work with several specimen geometries. Applications of the test method for screening of temperature-dependent crack growth behavior and model verification are discussed.

Gao et al. describe a unique thermal fatigue test rig fitted with a chamber that enables testing under various environments, including flowing hydrogen. The performance of the rig and the associated test procedures were evaluated through experimental testing of a γ TiAl alloy.

Dai et al. discuss thermal mechanical fatigue crack growth (TMFCG) results obtained for two titanium alloys. Tests were conducted using several strain-temperature phasings, and the ability of several fracture mechanics parameters to correlate the data was evaluated. Also, a model to predict TMFCG rates is presented and its application to estimate lives of engine components is discussed.

Titanium Matrix Composites

Over the past several years, silicon-carbon-fiber-reinforced titanium matrix composites (TMCs) have received considerable attention in the aeronautics and aerospace research communities for potential use in advanced high-temperature airframe and propulsion system applications. The obvious attractions of TMCs are the high stiffness and strength-to-weight ratios achievable at elevated temperatures, relative to current generation structural alloys. The papers included in the TMC section of this publication discuss many of the complex phenomenological behaviors and analytical modeling issues which arise under TMF loading conditions.

Coker et al. present a deformation analysis of a [0/90] TMC. A micromechanics approach is taken which treats the crossply as a three-constituent material consisting of a linear-elastic [0] fiber, a viscoplastic matrix in the [0] ply, and a viscoplastic [90] ply with damage to simulate fiber/matrix (f/m) interface separation, The authors clearly show the importance of treating the TMC as a thermoviscoplastic medium and the need to account for f/m separation when assessing [0/90] crossply macroscopic response. The contribution by Roberston and Mall features a modified Method of Cells micromechanics approach coupled with a unique f/m interface failure scheme based upon a probabalistic failure criterion. The proposed methodology incorporates the effects of both normal and shear f/m interface failures. Verification of the analysis is conducted under TMF loadings where the model appears to capture the progression of the interfacial damage with cycles.

Johnson et al. present a detailed experimental evaluation of the fatigue behavior of a [0/90] TMC subjected to a generic hypersonic flight profile. Material response under isolated segments of the flight profile are also examined to help identify critical combinations of load and time at temperature. Results indicate that sustained load at temperature had a more deleterious effect on fatigue life than that of a combined nonisothermal temperature profile and mechanical loading. Significant strain accumulations and eventual failure of the composite under sustained load conditions were found to result primarily from [90] f/m interface separation and sustained load crack growth, rather than more traditional creep mechanisms such as viscoplastic deformation of the matrix. Aksoy et al. also examine the fatigue performance of a TMC subjected to a mission cycle, but here the cycle was designed to simulate the stress-temperature-time profile in a TMC ring reinforced impeller of a turboshaft engine. Results indicate that although the 14-minute mission cycle life was found to be significantly less than that revealed under isothermal conditions at a much faster loading rate (as expected), the failure mechanisms appeared to be very similar.

The paper contributed by Neu extends the concept of mechanistic maps to TMCs and presents unique TMF damage mechanisms maps for unidirectional laminates loaded in the fiber direction. Extensive experimental data and observations are weighted to guide the use of adopted and derived life prediction models and specify mechanistic regions of the maps. Combined life and damage mechanism maps are then constructed over a wide range of stress and temperature using the characterized prediction models. Ball presents experimental results on both [0] and [0/90] TMCs, along with a continuum damage-mechanics-based lifing approach. Damage is incorporated into the material constitutive equations at the ply level prior to the use of classical lamination theory to obtain the laminate response. Three types of damage are considered, including fiber breakage, f/m debonding, and matrix microcracking.

Nicholas and Johnson present a systematic study of the potential interactions between cyclic fatigue and creep (superimposed hold times) in [0] and [0/90] TMCs. Cyclic conditions involving low-frequency cycling and/or hold times at relatively high temperatures were found to result in failures dominated by time-dependent mechanisms with little or no contribution from fatigue-induced failure mechanisms. This observation was elucidated through a linear damage summation model which treats cycle- and time-dependent mechanisms separately. Blatt et al. also employ a linear summation model, but here in the context of understanding and predicting fatigue crack growth (FCG) rates. A unique study is presented examining the FCG behavior of a unidirectional TMC under TMF conditions. Results indicate that the amount of cycle time spent at or near T_{max} conditions was a key factor influencing the FCG rate. The proposed model appeared to be successful at predicting the FCG rate of a proof test involving a continually changing temperature and load range to produce a constant FCG rate.

Concluding Remarks

We feel that the work presented here is an outstanding reflection of the latest research in this demanding field and a noteworthy contribution to the literature. The contributions from both U.S. and international authors give a global perspective of the concerns and approaches. Finally, we would like to express our gratitude to the authors, reviewers, and ASTM staff for their hard work and resulting contributions to this STP.

Michael J. Verrilli

Symposium co-chairman and co-editor; NASA Lewis Research Center, Cleveland, Ohio.

Michael G. Castelli

Symposium co-chairman and co-editor; NYMA, Inc., NASA LeRC Group, Brook Park, Ohio.

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