# FRACTOGRAPHY OF MODERN ENGINEERING MATERIALS

**Composites and Metals** 



# FRACTOGRAPHY OF MODERN ENGINEERING MATERIALS: COMPOSITES AND METALS

A symposium sponsored by ASTM Committees E-24 on Fracture Testing and D-30 on High Modulus Fibers and Their Composites Nashville, TN, 18–19 Nov. 1985

ASTM SPECIAL TECHNICAL PUBLICATION 948 John E. Masters, American Cyanamid Co., and Joseph J. Au, Sundstrand Corp., editors

ASTM Publication Code Number (PCN) 04-948000-30



#### Library of Congress Cataloging-in-Publication Data

Fractography of modern engineering materials.

(ASTM special technical publication; 948)

"Papers presented at the Symposium on Fractography of Modern Engineering Materials"—Foreword.

"ASTM publication code number (PCN) 04-948000-30." Includes bibliographies and index.

1. Fractography—Congresses. 2. Composite materials—Fracture—Congresses. 3. Metals—Fracture—Congresses. 1. Masters, John E. II. Au, Joseph J. III. ASTM Committee E-24 on Fracture Testing. IV. ASTM Committee D-30 on High Modulus Fibers and Their Composites. V. Symposium on Fractography of Modern Engineering Materials (1985: Nashville, Tenn.) VI. Series. TA409.F683 1987 620.1'126 87-14970 ISBN 0-8031-0950-4

Copyright © by American Society for Testing and Materials 1987 Library of Congress Catalog Card Number: 87-14970

#### NOTE

The Society is not responsible, as a body, for the statements and opinions advanced in this publication.

## **Foreword**

This publication, Fractography of Modern Engineering Materials: Composites and Metals, contains papers presented at the Symposium on Fractography of Modern Engineering Materials, which was held in Nashville, Tennessee, 18–19 Nov. 1985. The symposium was sponsored by ASTM Committees E-24 on Fracture Testing and D-30 on High Modulus Fibers and Their Composites. John E. Masters, American Cyanamid Co., and Joseph J. Au, Sundstrand Corp., presided as symposium chairmen and were editors of this publication.

# Related ASTM Publications

Composite Materials: Fatigue and Fracture, STP 907 (1986), 04-907000-33 Delamination and Debonding of Materials, STP 876 (1985), 04-876000-33 Short Fiber Reinforced Composite Materials, STP 772 (1982), 04-772000-30 Fracture Mechanics of Composites, STP 593 (1976), 04-593000-33

# A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

## **ASTM Editorial Staff**

David D. Jones Janet R. Schroeder Kathleen A. Greene Bill Benzing

# Contents

Overview

| Keynote Address  |                 |
|--|-----------------|
| Fracture Surface Micromorphology in Engineering Solids—R. W. HERTZBERG   | 5               |
| Composites   |                 |
| Composites I: Delamination   |                 |
| SEM Fractography of Pure and Mixed-Mode Interlaminar Fractures in Graphite/Epoxy Composites—L. ARCAN, M. ARCAN, AND I. M. DANIEL               | 41              |
| Correlations Between Micromechanical Failure Processes and the Delamination Toughness of Graphite/Epoxy Systems— M. F. HIBBS AND W. L. BRADLEY | 68              |
| Composites II: Structures  |                 |
| Fracture Characteristics of Angleplied Laminates Fabricated from Overaged Graphite/Epoxy Prepreg—C. A. GINTY AND C. C. CHAMIS                  | 01              |
|  | e<br> 31<br> 53 |
| Determination of Crack Propagation Directions in Graphite/Epoxy Structures—B. W. SMITH AND R. A. GROVE   | 54              |

1

### Composites III: Particulate Composites

| Microstructural Aspects of Crack Propagation in Filled Polymers—<br>G. M. NEWAZ  | 177 |
|--|-----|
| A Fractographic Study of Damage Mechanisms in Short-Fiber Metal Matrix Composites—D. H. ALLEN, C. E. HARRIS, E. W. NOTTORF, AND G. G. WREN                   | 189 |
| Composites IV: Environmental Effects   |     |
| Fracture Surfaces of Irradiated Composites—S. M. MILKOVICH, G. F. SYKES, JR., AND C. T. HERAKOVICH   | 217 |
| Characterization of Impact Damage Development in Graphite/Epoxy Laminates—J. E. MASTERS  | 238 |
| METALS   |     |
| Feature Identification   |     |
| Fractographic Feature Identification and Characterization by Digital Imaging Analysis—R. W. GOULD AND R. H. McSWAIN  | 263 |
| Metals I: Ferrous Alloys   |     |
| Fractography of Pressure Vessel Steel Weldments—J. SANKAR, D. B. WILLIAMS, AND A. W. PENSE   | 295 |
| A Fractographic Investigation of Fatigue Damage in Carburized Steel—G. M. NEWAZ  | 317 |
| Fracture Morphology of 13% Chromium Steam Turbine Blading Steel—S. K. BHAMBRI  | 334 |
| Fractographic Studies of the Ductile-to-Brittle Transition in Austenitic Stainless Steels—T. A. PLACE, T. S. SUDARSHAN, C. K. WATERS, AND M. R. LOUTHAN, JR. | 350 |
| Fractography in the Failure Analysis of Corroded Fracture Surfaces— A. O. IBIDUNNI   | 366 |

## Metals II: Nonferrous Alloys

| Micromechanisms of Major/Minor Cycle Fatigue Crack Growth in       |     |
|--|-----|
| Inconel 718—S. VENKATARAMAN, T. NICHOLAS, AND N. E. ASHBAUGH       | 383 |
| Fractographic Analysis of Hydrogen-Assisted Cracking in Alpha-Beta |     |
| Titanium Alloys—D. A. MEYN AND R. A. BAYLES                        | 400 |
| Fractographic Aspects of the Effect of Environment on the Fatigue  |     |
| Crack Propagation Mechanism in a High-Strength Aluminum            |     |
| Alloy—N. RANGANATHAN, B. BOUCHET, AND J. PETIT                     | 424 |
| Indexes  | 447 |