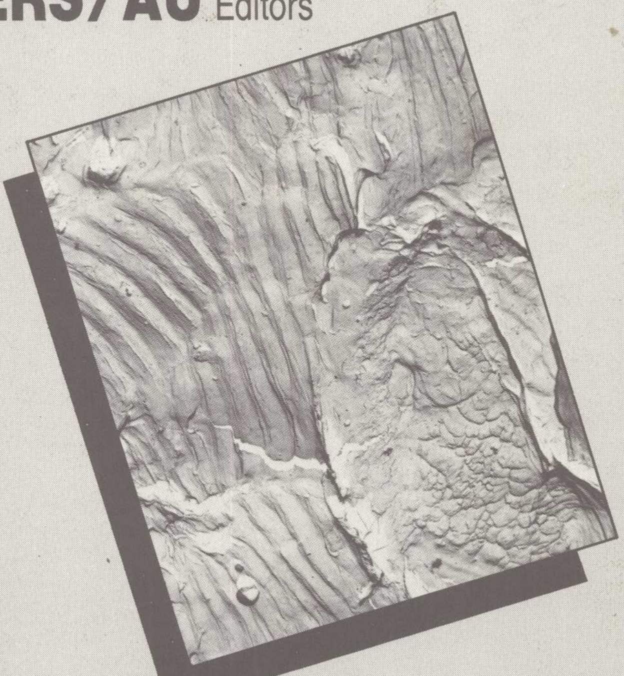
FRACTOGRAPHY OF MODERN ENGINEERING MATERIALS

Composites and Metals

MASTERS/AU Editors



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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
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Nashville, TN, 18–19 Nov. 1985

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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.

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Overview

Fractography is the detailed analysis of a fracture surface to determine the cause of the fracture and the relationship of the fracture mode to the microstructure of the material. Fractography techniques are used, for example, to identify the origin of a crack and to determine what type of loading caused the crack to initiate. They are also used to establish the direction of crack propagation and the local loading mode which drove the crack. Fractography is, perhaps, the most important analytical approach used by materials scientists in attempting to establish structure-property relationships involving strength and failure of materials.

The science of fractography has been developed into a tool which can be applied to all phases of material investigation. It plays a key role in the failure analysis of established materials. Fractography can also provide useful information in evaluating new materials and in defining their response to mechanical, chemical, and thermal environments.

The technological challenges of recent developments in the aircraft, power generation, and communications industries have led to the development and application of numerous advanced, high-performance materials. These include carbon fiber-reinforced composites, high-strength steel and nonferrous alloys, and superalloys. In addition to design requirements which demand increased strength and stiffness, these new materials are often subjected to harsh fatigue and environmental conditions which may limit their lives. Unfortunately, the development of the fractographic data required to interpret the failure modes of these materials has not always kept pace with their rapid advancement.

The objective of the Symposium on Fractography of Modern Engineering Materials was to provide a forum for presentation and discussions of results of fractographic investigations of these emerging materials. An excellent overview of this topic was presented by Professor R. W. Hertzberg of Lehigh University in his keynote address entitled "Fracture Surface Micromorphology in Engineering Solids."

In addition to the keynote address, 22 papers were presented at the symposium, which was jointly sponsored by ASTM Committees E24 on Fracture Testing and D30 on High Modulus Fibers and Their Composites. These presentations were divided equally between the fractography of metallic and composite materials. The bulk of the work presented on the latter topic discussed failure of continuous fiber graphite/epoxy material systems. This included several presentations on delamination propagation in these materials. The effects of impact and radiation damage on these systems and the fracture surface characterization of notched laminates were also reviewed. The fractography of ferrous alloys comprised the majority of the papers presented on metallic materials. This included discussions of the fractography of steam turbine blading steels, steel weldments in pressure vessels, fatigue damage in carburized steel, and ductile-brittle transition in austenitic stainless steels. In addition, papers were also presented on fatigue crack growth in Inconel and high-strength aluminum alloys and on hydrogen-assisted cracking in titanium alloys.

The expanded use of all of these materials and the increasingly severe loading and service environments to which they are exposed necessitates a thorough knowledge of their fracture behavior. This is particularly true, for example, of composite materials since they are now being used in primary structural applications in the aircraft industry. The ability to correctly interpret the material's fracture mechanisms and to define component failure modes is critical in determining air worthiness and in investigating in-service component failure. The situation in this case is further complicated because these materials exhibit failure modes not normally encountered in metallic materials due to their anisotropic and heterogeneous nature.

It is hoped that the papers presented in this volume will aid investigators conducting failure analyses of advanced composite and metallic materials. It is also hoped that additional symposia will be held as this body of knowledge continues to be developed.

The editors would like to gratefully acknowledge the many contributions provided to this volume by the authors, the reviewers, and the ASTM staff.

John E. Masters

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Keynote Address

Richard W. Hertzberg[1]

Fracture Surface Micromorphology in Engineering Solids

REFERENCE: Hertzberg, R. W., "**Fracture Surface Micromorphology in Engineering Solids,**" *Fractography of Modern Engineering Materials: Composites and Metals, ASTM STP 948*, J. E. Masters and J. J. Au, Eds., American Society for Testing and Materials, Philadelphia, 1987, pp. 5–36.

ABSTRACT: The macroscopic and microscopic features of fracture surfaces in metal alloys, polymeric solids, and their composites are examined with particular attention given to the appearance of fatigue damage micromorphology. Macroscopic features such as chevron markings, shear lips, and fatigue clam shell bands and ratchet lines are observed in metal and polymer alloys and are useful in identifying the crack origin, direction of crack growth, and stress state. Certain micromechanisms are common to both metals and plastics (for example, microvoid coalescence, interfacial separation, river markings, and fatigue striations), whereas other fracture markings are unique to a particular material as a result of different microstructures and deformation processes (for example, craze fracture markings and discontinuous growth bands). In general, fracture surface features are seen to depend on the magnitude of the crack driving force, scale of the microstructure relative to the crack tip plastic zone size, and the viscoelastic state of the material.

KEYWORDS: fractography, fatigue, polymers, metals, composites, microstructure, deformation mechanisms, crazing

Much can be learned from an assessment of one's past mistakes. This is particularly true when one examines the details found on a fracture surface. For example, fracture surface markings often reveal the crack origin, the direction of crack propagation, and the stress state that prevailed during the fracture event. Observations of this kind have been reported in various journal articles and conference proceedings, and are contained in several handbooks devoted to the subject of fracture surface analysis [*1–7*].

Though a detailed fractographic examination in either the transmission or scanning electron microscope (SEM) provides a wealth of useful information pertaining to the failure event, this author firmly believes that

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the initial step in any fractographic analysis should involve a macroscopic examination of a given fracture surface. In this manner, the investigator gains an overview of the progression of the crack(s), and this enables him/her to focus attention on the critical initiation site instead of on the fast fracture region that usually accounts for much of the total fracture surface area generated. Accordingly, some discussion will be focused on an analysis of several commonly observed macrofractographic features that provide information concerning the stress state, crack origin(s), and direction of crack growth in metal and plastic alloys, respectively.

Since much has been written elsewhere on the subject of electron fractography of metal alloys [*1–6*], brief mention of common fracture surface markings will suffice; the remainder of the paper is devoted to a study of fracture processes in emerging structural materials such as engineering plastics and their composites. Particular attention is given to an analysis of the fatigue fracture surface micromorphology of metals, plastics, and their composites since most service failures involve cyclic stresses and/or strains.

Preparation Procedures

In preparation for an electron fractographic examination of a particular fracture, one should conduct both a macroscopic examination of the fracture surface and a detailed examination of the underlying microstructure of the material in question. Surely, the fracture surface markings reflect the underlying microstructure to the extent that the crack path either prefers or avoids certain microconstituents. Chestnutt and Spurling [*8*] demonstrated effectively that one could simultaneously examine the fracture surface and identify the underlying microstructure. Their procedure involved masking part of the fracture surface with a lacquer and then electropolishing the exposed portions of the fracture surface. After removing the lacquer, the specimen is analyzed in the SEM so as to reveal *both* microstructural and fractographic features. An example of this technique is shown in Fig. 1, which reveals elongated microvoid coalescence in an aluminum (Al)–nickel aluminite (Al_3Ni) eutectic composite. The microvoids were nucleated by rupture of Al_3Ni whiskers (see arrows).

To be sure, a fractographic examination must be preceded by careful cleaning of the fracture surface. Zipp [*9*] has cited several cleaning procedures that include benign techniques such as: dry air blasting to remove loosely adhering particles; the use of various cleaning fluids such as acetone and toluene to remove greases and oils; and repeated stripping of the fracture surface with cellulose acetate replicating tape for removal of tenacious films. When such procedures are found wanting in the case of badly corroded fracture surfaces, more aggressive techniques are needed. In this regard, Zipp

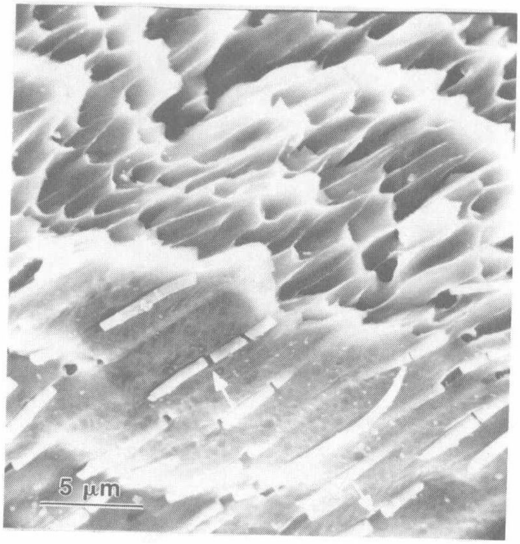

FIG. 1—*Fracture surface (top) and microstructural (bottom) appearance of Al-Al_3Ni eutectic composite. Stopoff lacquer applied to fracture surface, and specimen electropolished in 0.5% HF + H_2O solution. Arrows indicate fractured Al_3Ni whiskers. (Photograph courtesy of K. Vecchio.)*

has recommended that a degraded fracture surface be placed in a bath containing an Alconox cleaning solution (15 g Alconox powder + 350 cm^3 water), which is then heated to 95°C and agitated ultrasonically. Vecchio and Hertzberg [*10*] have found that the sample should not be exposed to this bath for more than 15 to 30 min to prevent chemical attack of the fracture surface.

It should be noted that the use of cleaning solvents may be suitable for metal alloys, but are unsuitable for use with most plastics and their composites since these organic fluids either dissolve or severely attack the polymer structure. Furthermore, the mechanical action of stripping replica tapes (water soluble polyacrylic acid in this instance) from a polymer fracture introduces undesirable artifacts [*11*]. Problems may also be encountered when polymer fracture surfaces are examined in the SEM. Depending on the thermal stability of the polymer and the thickness of the metal coating, the electron beam may alter the fracture surface micromorphology and even cause localized melting. Figure 2 shows a region on the fatigue fracture surface of polymethyl methacrylate (PMMA) that was damaged during reduced area imaging for the purpose of focus optimization [*12*]. In some instances, when excessive beam potential or current is applied, fissures may develop in conjunction with the presence of internal stresses [*13*].