# FRACTOGRAPHY AND MATERIALS SCIENCE

Gilbertson/Zipp, *editors*

ASTM STP 733

AMERICAN SOCIETY FOR TESTING AND MATERIALS

# FRACTOGRAPHY AND MATERIALS SCIENCE



A symposium
sponsored by
ASTM Committee E-24
on Fracture Testing
AMERICAN SOCIETY FOR
TESTING AND MATERIALS
Williamsburg, Va., 27–28 Nov. 1979

ASTM SPECIAL TECHNICAL PUBLICATION 733
L. N. Gilbertson, Zimmer, U.S.A., and
R. D. Zipp, International Harvester,
editors

ASTM Publication Code Number (PCN)
04-733000-30

AMERICAN SOCIETY FOR TESTING AND MATERIALS
1916 Race Street, Philadelphia, Pa. 19103

Library of Congress Catalog Card Number: 80-69750

NOTE

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

Printed in Baltimore, Md.
May 1981

# Foreword

The symposium on Fractography and Materials Science was held on 27–28 Nov. 1979 in Williamsburg, Va. The American Society for Testing and Materials, through its Committee E-24 on Fracture Testing and Subcommittee E24.02 on Fractography and Associated Microstructures, sponsored the event. The symposium chairmen were L. N. Gilbertson, Zimmer, U.S.A., and R. D. Zipp, International Harvester, both of whom also served as editors of this publication.

# Related ASTM Publications

Crack Arrest Methodology and Applications, STP 711 (1980), $44.75, 04-711000-30

Fracture Mechanics: Twelfth Conference, STP 700 (1980), $53.25, 04-700000-30

Fracture Mechanics Applied to Brittle Measurements, STP 678 (1979), $25.00, 04-678000-30

Fracture Mechanics: Eleventh Conference, STP 677 (1979), $60.00, 04-677000-30

Elastic-Plastic Fracture, STP 668 (1979), $58.75, 04-668000-30

Fractography in Failure Analysis, STP 645 (1978), $36.50, 04-645000-30

Developments in Fracture Mechanics Test Methods Standardization, STP 632 (1977), $24.75, 04-632000-30

Fractography—Microscopic Cracking Process, STP 600 (1976), $27.50, 04-600000-30

Toughness and Fracture Behavior of Titanium, STP 651 (1978), $28.50, 04-651000-30

Evaluations of the Elevated Temperature Tensile and Creep Rupture Properties of 12 to 27 Percent Chromium Steels, DS 59 (1980), $24.00, 05-059000-40

# A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge with appreciation their contribution.

*ASTM Committee on Publications*

# Editorial Staff

# Contents

# Introduction

This symposium was organized to demonstrate the importance of utilizing state-of-the-art and new fractographic principles in materials science. These principles are applied in the upcoming text to a variety of metals, including iron, aluminum, titanium, copper, nickel, and tungsten-base alloys, and various nonmetals, including polymers, ceramics, and glasses.

The papers contained in this volume demonstrate that fracture analysis is more than just examination of the fracture surface. Variables such as the microstructure, stress conditions, and the environment control the fracture surface topography in materials. All of the papers presented here discuss at least one of these variables and its influence on the resulting fracture morphology. By correlating these variables with fractography, a more complete and detailed understanding of fracture characteristics in materials is made possible. This is necessary to comprehend more fully the complexities involved in fracture processes.

This volume should serve as a background reference and a guide for investigators interested in evaluating fracture surface topographies for a variety of materials. The high degree of sophistication needed to interpret complex fractographs should become evident as the reader becomes familiar with this document. We believe that the information contained within provides a firm foundation for continued advancement in fractography and demonstrates the level of refinement that has taken place recently in this field. We also think that the work presented here can be still further refined to provide for better understanding of fracture behavior in materials.

*L. N. Gilbertson*
Zimmer, U.S.A., Warsaw, Ind. 46580; symposium chairman and editor.

*R. D. Zipp*
International Harvester, Hinsdale, Ill. 60521; symposium chairman and editor.

# Environment

*D. A. Meyn*[1] *and E. J. Brooks*[1]

# Microstructural Origin of Flutes and Their Use in Distinguishing Striationless Fatigue Cleavage from Stress-Corrosion Cracking in Titanium Alloys

**REFERENCE:** Meyn, D. A. and Brooks, E. J., "**Microstructural Origin of Flutes and Their Use in Distinguishing Striationless Fatigue Cleavage from Stress-Corrosion Cracking in Titanium Alloys,**" *Fractography and Materials Science, ASTM STP 733,* L. N. Gilbertson and R. D. Zipp, Eds., American Society for Testing and Materials, 1981, pp. 5-31.

**ABSTRACT:** Postfracture analysis does not always distinguish striationless low-stress fatigue from stress-corrosion cracking (SCC), since both are characterized by cleavage, together with other less distinct fracture modes. Studies of identical specimens of Ti-8Al-1Mo-1V broken under both conditions suggest that the presence of certain microplastic fracture features called flutes may be uniquely characteristic of SCC, and absent from low-stress striationless fatigue fractures. Some new observations concerning the microstructural origins of flutes verify that they arise from a tendency toward planar slip in $\alpha$ and $\alpha$–$\beta$ alloys and from the presence of multiple cleavage during crack propagation under certain circumstances, including SCC.

**KEY WORDS:** titanium alloys, stress-corrosion cracking, fatigue, fractography, fracture mechanisms, cleavage, flutes, hydrogen embrittlement, sustained load cracking, materials science, materials

Both aqueous stress-corrosion cracking (SCC) and low-stress fatigue cracking (LSFC) in alloys that are susceptible to SCC, such as Ti-8Al-1Mo-1V, create substantially similar fracture surfaces that consist mostly of cleavage facets. Under sufficiently low cyclic crack-tip stresses, LSFC leaves no striations to serve as unmistakable signs of fatigue. Hence, failure analysis in these alloys can be uncertain where the fracture surface consists mainly of cleavage. Differentiation between the two cracking mechanisms can often be made by experienced fractographic analysts by noting a smoothed, tear-ridge–free appearance in LSFC, in contrast with a greater abundance of tear ridges and somewhat more microplastic deformation at cleavage facet boundaries in

[1] Metallurgists Naval Research Laboratory, Washington, D.C. 20375.

SCC. However, more cut-and-dried qualitative differences are preferable in making such distinctions.

A feature of SCC fracture surfaces of α and α–β titanium alloys, once mistaken for cleavage [*1*],[2] but since identified as flutings [*2*], river patterns [*3, 4*], and striations [*5*], seems to provide such a qualitative differentiation. The term "flutes" is preferred for these features as it avoids confusion with other applications for the latter two terms.

Not all those who use fractography for materials research or failure analysis understand exactly what flutes are and what causes them to form. Some new observations of fluting under conditions of mechanical overload fracture, SCC, sustained load cracking (SLC) in inert environments, fatigue, and corrosion fatigue conditions will be presented to familiarize readers with a variety of flute characteristics and to provide new information concerning fluting mechanisms and the conditions that give rise to fluting. The following discussion includes a review of significant prior work, a summation of conditions and parameters important to flute formation, some comments on mechanisms of flute initiation and formation, and, finally, an assessment of the significance of flutes as a diagnostic fractographic feature in α and α–β titanium alloys.

## Materials and Methods

### *Materials*

A review of numbers of fractographs in the literature made it clear that flutes produced by SCC look similar in most near-α and α–β alloys such as Ti-5Al-2.5Sn, Ti-8Al-1Mo-1V, and Ti-6Al-4V. Alloy Ti-8Al-1Mo-1V was therefore selected for flute fractography studies in two metallurgical conditions: the β-annealed and furnace-cooled and the as-received "mill-annealed" condition. One other alloy of unusually high interstitial content, Ti-0.35O was chosen for examination of flutes formed under mechanical overload conditions.

The microstructures of both the beta-annealed (βA) and the mill-annealed (MA) Ti-8Al-1Mo-1V material are shown in Fig. 1. The βA material consists mainly of colonies or packets of similarly aligned α plates, with interplate β-phase. This is usually called coarse Widmanstätten alpha. The colonies or packets behave like single grains in many respects; for example, large cleavage facets consist of cleavage on a common plane through all the plates in a single facet, since they are all of essentially the same crystallographic orientation within a colony. However, the β-phase between the alpha plates does not cleave, and this constitutes a site for diversion of cracks. The MA material contains some fine Widmanstätten-like microstructures, but it consists mostly of a mixture of primary alpha (irregular grains) and so-called transformed

[2] The italic numbers in brackets refer to the list of references appended to this paper.

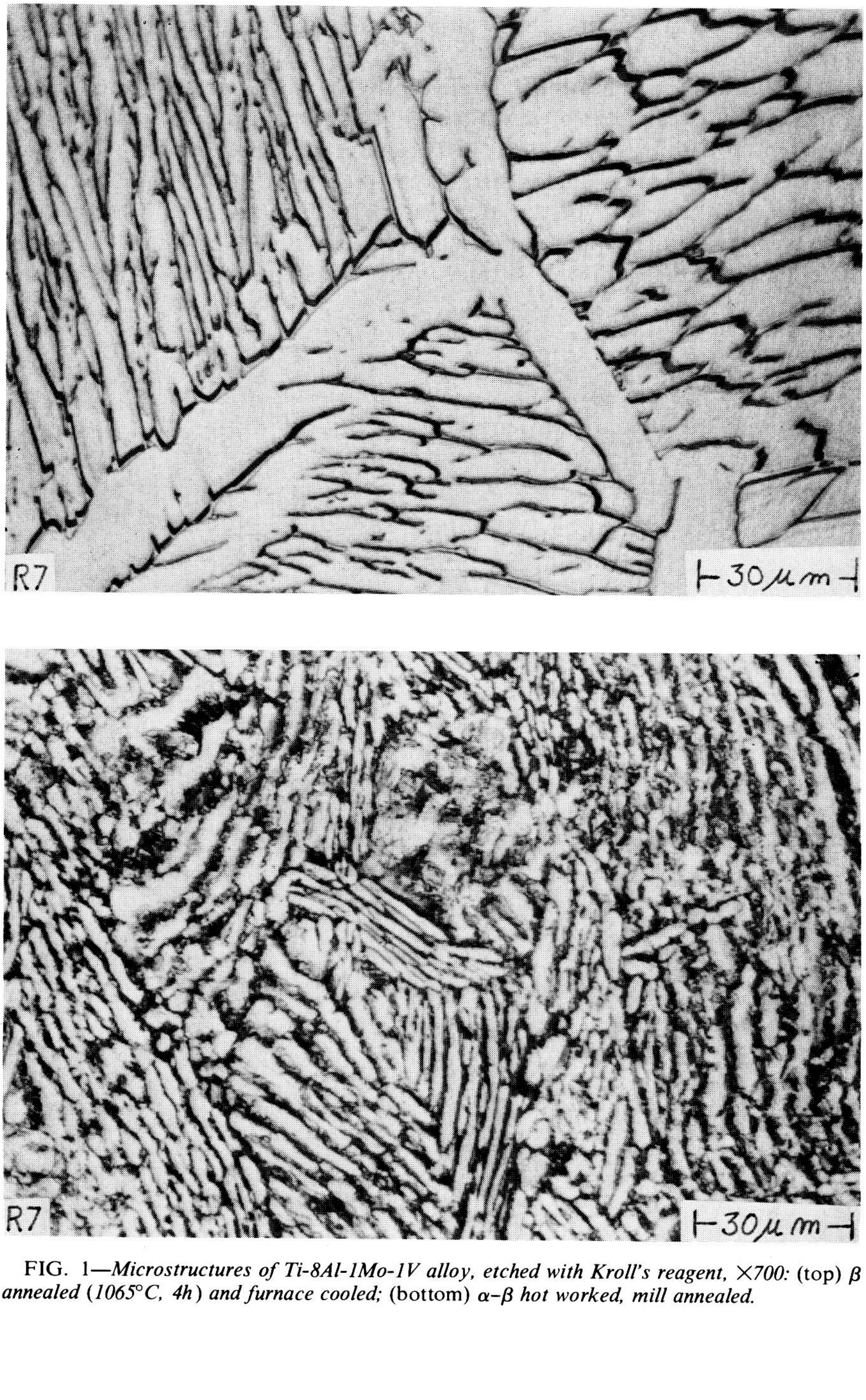


FIG. 1—*Microstructures of Ti-8Al-1Mo-1V alloy, etched with Kroll's reagent, ×700:* (top) $\beta$ *annealed (1065°C, 4h) and furnace cooled;* (bottom) $\alpha$–$\beta$ *hot worked, mill annealed.*

beta, a fine dispersion of alpha-phase in a skimpy beta matrix. The Ti-0.35O alloy (not shown) consists of very large angular and platelike grains with no $\beta$-phase.

The following presentation will refer both to $\alpha$ plates, which are platelike $\alpha$ grains, and to cleavage plates, which result from multiple cleavage through one or more $\alpha$ grains to produce partly isolated cleavage elements. This is illustrated in Fig. 2 for a single plate-shaped $\alpha$ grain, with some other features whose significance will be apparent later. In the hexagonal close-packed (HCP) crystal of the $\alpha$-phase, the (0001) planes are often called basal planes, and planes and generalized surfaces perpendicular to (0001) are termed prismatic.

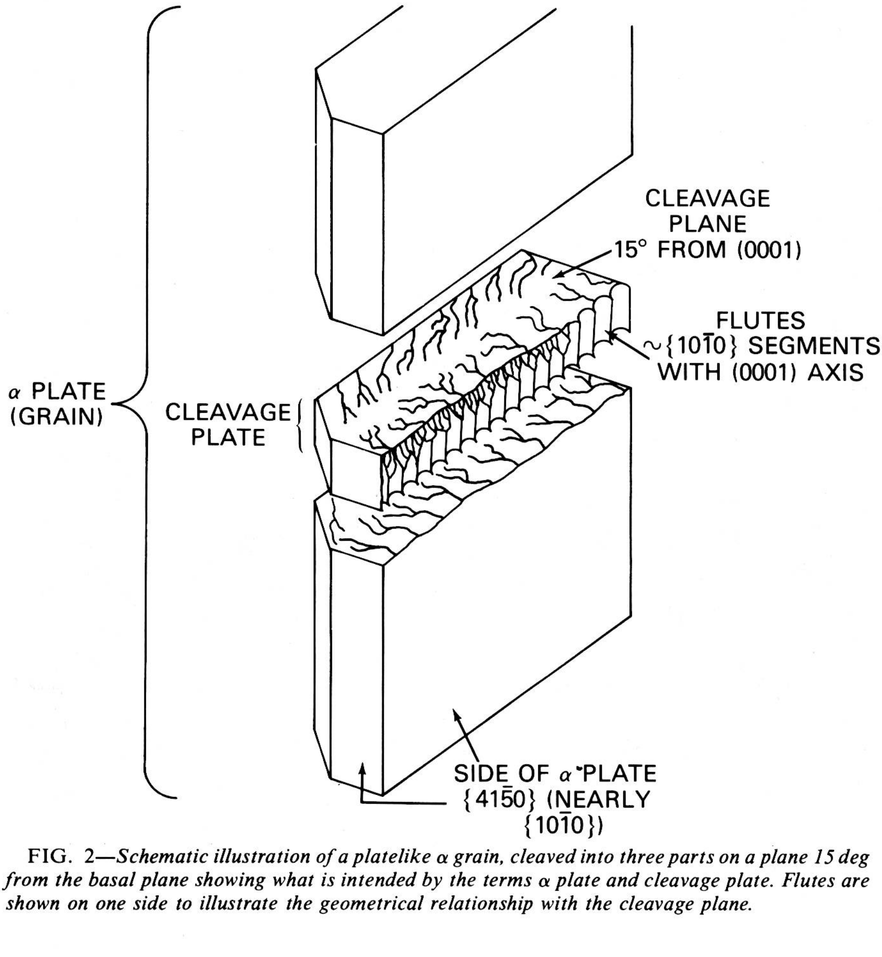


FIG. 2—*Schematic illustration of a platelike α grain, cleaved into three parts on a plane 15 deg from the basal plane showing what is intended by the terms α plate and cleavage plate. Flutes are shown on one side to illustrate the geometrical relationship with the cleavage plane.*