ASM Handbook®

Volume 11
Failure Analysis and Prevention

Prepared under the direction of the
ASM International Handbook Committee

William T. Becker and Roch J. Shipley, Volume Editors

Steven R. Lampman, Project Editor
Bonnie R. Sanders, Manager of Production
Gayle J. Anton, Editorial Assistant
Nancy Hrivnak, Jill Kinson, and Carol Terman, Production Editors
Kathryn Muldoon, Production Assistant
Scott D. Henry, Assistant Director of Technical Publications
William W. Scott, Jr., Director of Technical Publications

Editorial Assistance
Elizabeth Marquard
Heather Lampman
Mary Jane Riddlebaugh

ASM International®
The Materials Information Society

Materials Park, Ohio 44073-0002
www.asminternational.org

First printing, December 2002

Comments, criticisms, and suggestions are invited, and should be forwarded to ASM International

Library of Congress Cataloging-in-Publication Data

ASM International

ASM Handbook
Includes bibliographical references and indexes
Contents: v.1. Properties and selection—irons, steels, and high-performance alloys—v.2. Properties and selection—nonferrous alloys and special-purpose materials—[etc.]—v.21. Composites

1. Metals—Handbooks, manuals, etc. 2. Metal-work—Handbooks, manuals, etc. I. ASM International. Handbook Committee.
II. Metals Handbook.
TA459.M43 1990 620.1′6 90-115
SAN: 204-7586
ISBN: 0-87170-704-7

ASM International®
Materials Park, OH 44073-0002
www.asminternational.org

Printed in the United States of America

Multiple copy reprints of individual articles are available from Technical Department, ASM International.

Foreword

This 2002 edition of *Failure Analysis and Prevention* is the outcome from the devoted efforts of volunteer editors, authors, and reviewers, who have helped organize and develop this revised Volume 11 of the *ASM Handbook* series. This publication would not have been possible without their vision and dedicated efforts in the ongoing improvement of engineering knowledge and education through the analysis, understanding, and prevention of failure.

As noted in the Preface, the authors and editors assembled this Volume with several broad themes in mind. The nature of failure is complex, varied, and unanticipated. Its prevention can also be multifaceted and varied. In this way, failure analysts are not only specialists, but also educators who help others become aware of the root cause(s) of failure. This requires a clear understanding of the many stages in the life of a part from design and manufacturing to anticipated service, inspection, and maintenance. It also involves a host of tools and techniques for effective planning and implementation of a failure investigation.

Thus, failure analysis and prevention can be a complex multidisciplinary activity that requires broad knowledge in design, manufacturing, mechanics, materials, and testing. The editors and authors have tackled this complex nature of failure analysis and prevention in an updated volume that is, in many respects, an all-new volume. This new edition contains over 50 new articles with expanded coverage on the four basic types of failures (deformation, fracture, corrosion, and wear) and the variety of tools and techniques for effective planning, organization, implementation, and reliable conclusion of a failure investigation through proper interpretation of information.

We would like to extend our thanks to the devoted community of volunteers who have helped organize and develop this 2002 edition of *Failure Analysis and Prevention.* The editors, authors, and reviewers are to be commended for their fine contributions on a vital topic for all engineering disciplines, in the very best of tradition of the Handbook series. We especially thank Bill Becker, Roch Shipley, Debbie Aliya, Dan Benac, Larry Hanke, Jeff Hawk, Steve McDanels, Richard McSwain, Ron Parrington, Jim Scutti, Aaron Tanzer, and Richard Wilson. This publication would not have been possible without their vision, knowledge, and efforts.

Gordon H. Geiger
President
ASM International

Stanley C. Theobald
Managing Director
ASM International

Policy on Units of Measure

By a resolution of its Board of Trustees, ASM International has adopted the practice of publishing data in both metric and customary U.S. units of measure. In preparing this Handbook, the editors have attempted to present data in metric units based primarily on Système International d'Unités (SI), with secondary mention of the corresponding values in customary U.S. units. The decision to use SI as the primary system of units was based on the aforementioned resolution of the Board of Trustees and the widespread use of metric units throughout the world.

For the most part, numerical engineering data in the text and in tables are presented in SI-based units with the customary U.S. equivalents in parentheses (text) or adjoining columns (tables). For example, pressure, stress, and strength are shown both in SI units, which are pascals (Pa) with a suitable prefix, and in customary U.S. units, which are pounds per square inch (psi). To save space, large values of psi have been converted to kips per square inch (ksi), where 1 ksi = 1000 psi. The metric tonne (kg $\times$ 10^3) has sometimes been shown in megagrams (Mg). Some strictly scientific data are presented in SI units only.

To clarify some illustrations, only one set of units is presented on artwork. References in the accompanying text to data in the illustrations are presented in both SI-based and customary U.S. units. On graphs and charts, grids corresponding to SI-based units usually appear along the left and bottom edges. Where appropriate, corresponding customary U.S. units appear along the top and right edges.

Data pertaining to a specification published by a specification-writing group may be given in only the units used in that specification or in dual units, depending on the nature of the data. For example, the typical yield strength of steel sheet made to a specification written in customary U.S. units would be presented in dual units, but the sheet thickness specified in that specification might be presented only in inches.

Data obtained according to standardized test methods for which the standard recommends a particular system of units are presented in the units of that system. Wherever feasible, equivalent units are also presented. Some statistical data may also be presented in only the original units used in the analysis.

Conversions and rounding have been done in accordance with IEEE/ASTM SI-10, with attention given to the number of significant digits in the original data. For example, an annealing temperature of 1570 °F contains three significant digits. In this case, the equivalent temperature would be given as 855 °C; the exact conversion to 854.44 °C would not be appropriate. For an invariant physical phenomenon that occurs at a precise temperature (such as the melting of pure silver), it would be appropriate to report the temperature as 961.93 °C or 1763.5 °F. In some instances (especially in tables and data compilations), temperature values in °C and °F are alternatives rather than conversions.

The policy of units of measure in this Handbook contains several exceptions to strict conformance to IEEE/ASTM SI-10; in each instance, the exception has been made in an effort to improve the clarity of the Handbook. The most notable exception is the use of g/cm^3 rather than kg/m^3 as the unit of measure for density (mass per unit volume).

SI practice requires that only one virgule (diagonal) appear in units formed by combination of several basic units. Therefore, all of the units preceding the virgule are in the numerator and all units following the virgule are in the denominator of the expression; no parentheses are required to prevent ambiguity.

Preface

Welcome to the new edition of *ASM Handbook,* Volume 11, *Failure Analysis and Prevention.*

Theme and Purpose of this Volume. The authors and editors assembled this Volume with several broad themes in mind. First, the most important goal of failure analysis is to decrease the occurrence of component failures through the understanding of the root cause for failure. Experienced failure analysts are often frustrated when, despite extensive engineering research, investigations, and failure analysis reports, the same types of failures occur again and again. When the root cause has been identified as defective global design rather than abuse or misuse, product quality and reliability is improved.

The failure analyst should strive to uncover the underlying or root (technical) cause of the failure. The fact that a specific component appears to have failed in some way does not automatically mean that the component itself is defective. The problem may lie in the way the component was used, inspected, or maintained. If it is truly defective, then the analysis should determine whether the defect originates in design, manufacture (fabrication and assembly), material selection/processing, or unexpected service environment.

This Volume provides a framework for investigating the above issues. In addition to sections devoted to design and manufacture, there are also sections on failures that occur through fracture, corrosion, and wear, as well as an article on failure through deformation. This Volume is also an attempt to address the principles, tools, techniques, and procedures necessary to plan, organize, and conduct a thorough investigation. Not every failure investigation is the same, and a failure root-cause analysis is more than a microstructural examination, a stress analysis, or a chemical corrosion analysis. All of these disciplines, as well as others, may be required to reach a root cause conclusion.

No single volume, no matter how comprehensive, can present all the information that may potentially be needed. The emphasis of this Volume is on general principles with the widest applicability to situations that the reader is likely to encounter. References and sources of further information are provided throughout. While some common types of components or equipment may be included in some detail, not every type of machine can be treated. The reader is encouraged, and in fact urged, to pursue additional sources of information so as to understand the function and history of the component, machine, or system that is under investigation.

Audience. One of the challenges in preparing a work of this type is the diversity of readership. Some readers are students and other novices who may be confronted with a failed part for the first time. They may be looking to the Handbook for guidance on where to start their analysis. Other readers are experienced practitioners, using the Handbook to verify or clarify a critical detail in their analysis. Thus, the contents of this Volume include the essential basics of failure analysis, as well as more advanced discussions from a research perspective.

The discussions of fracture mechanisms are an example of this approach to Handbook organization. The articles "Overload Failures" and "Fatigue Failures" are good starting points for readers wishing to begin their study of fracture. Examination of the fracture surface (when failure did result in fracture) at both the macro and micro scale provides considerable information pertinent to a failure investigation. This subject is introduced in the article "Overload Failures" with some discussion of the mechanisms that may be involved.

For some readers, these may be sufficient, if all they need is to identify the basic fracture mechanism. However, further study can sometimes allow the analyst to learn more about the circumstances of a fracture. Unfortunately, there are few instances in which a single fractographic feature is definitive in identifying a root cause (and to distinguish between abuse and defective design). Casual examination may not distinguish between fine details caused by different fracture processes. Consequently, a detailed study of the fracture surface at both the macroscale and microscale is helpful and may be critical in obtaining a root cause conclusion. The reader who desires a more detailed appreciation and thorough understanding should continue with the article "Fracture Appearance and Mechanisms of Deformation and Fracture" and the article "Stress Analysis and Fracture Mechanics." These articles introduce quantitative means to relate the fracture process to material properties and, therefore, are critical to distinguishing between abuse or misuse and inadequate quality. Finally, the article "Mechanisms and Appearances of Ductile and Brittle Fracture in Metals" provides a still more in-depth treatment on the detailed appearances at both the macroscale and microscale, with the intent of extracting the maximum possible information for root-cause failure analysis.

Differences of Opinion. Controversy is, perhaps, inherent in the very nature of failure analysis. If anything, that is even truer today when real or perceived failures are the subject of litigation. The authors have integrated thoughts on legal considerations into many of the articles. However, nothing here should be taken as legal advice. Those who are concerned regarding legal implications should consult competent counsel.

Furthermore, as every circumstance is somewhat unique, the Handbook should be used with care and should not be the sole source of information when critical decisions are to be made. Most articles include extensive references, which should be reviewed if further information is required.

The authors present analyses and interpretations based on scientific principles and experience. All of the articles have been reviewed and edited. However, there can be and still are differences of opinion among failure analysts regarding some issues. It is up to the reader to determine whether the information presented is applicable and helpful in a particular situation. Experienced analysts should be consulted if there is any doubt. Despite the best efforts of the authors, reviewers, and editors, the reader might find an area that could be improved. If so, please bring this to the attention of the ASM Editors so that your concern can be reviewed and, depending on the consensus of opinion, can be addressed in subsequent printings.

Collaborative Effort. This Volume reflects the efforts of many people. Except for ASM staff, all are volunteers. Many of the volunteers are fully employed and contributed their personal time to the project. Neither they nor their employers receive any compensation for their efforts, except for the satisfaction that accrues from being able to share what they have learned, prevent failures, and contribute to safer, more reliable products. The names of the authors, editors, reviewers, and ASM staff are acknowledged individually elsewhere in this Volume and are too numerous to list here. However, ASM Editor Steven Lampman does deserve special mention for his commitment, dedication, and patience, without which this Volume would not have become a reality.

It has been most enjoyable and professionally rewarding to work with all who were involved in this effort. On behalf of ASM and the readers of this Handbook, we express our appreciation to all for the time and effort expended and for their willingness to share their knowledge and lessons derived from experience. Many of the contributors have established national and international reputations in their respective fields. More than any words of appreciation in a Preface such as this, however, it is our hope that the Handbook itself will be a most fitting tribute to all participants, both now and into the future.

William T. (Bill) Becker
Consultant (retired, University of Tennessee)

Roch J. Shipley
Packer Engineering Inc.

Officers and Trustees of ASM International (2001–2002)

Members of the ASM Handbook Committee (2001–2002)

Previous Chairs of the ASM Handbook Committee

Authors and Contributors

Tom Adler
Albany Research Center

Rehan Ahmed
Heriot-Watt University

Debbie Aliya
Aliya Analytical

Stephen D. Antolovich
Washington State University

Roy G. Baggerly

Ray Bayer

William T. Becker

M. Belassel
Proto Manufacturing Limited

Daniel J. Benac
Bryant-Lee Associates

Jayashree Bijwe
Indian Institute of Technology, Delhi

R.R. Blackwood
Tenaxol Inc.

John B. Bowles
University of South Carolina

M.E. Brauss
Proto Manufacturing Limited

Charlie Brooks
University of Tennessee

Mohan D. Chaudhari
Columbus Metallurgical Service

Yan-Ming Chen
CETIM

Ashok Choudhury
Lockheed Martin Energy Research

Scott S. Chumbley
Ames Laboratory

Carl Czajkowski
Brookhaven National Laboratory

Daniel R. Danks
Danks Tribological Services

Daniel P. Dennies
The Boeing Company

Bill Dobson
Binary Egnineering Associates, Inc.

Don Duvall
Engineering Systems Inc.

Rob Dwyer-Joyce
The University of Sheffield

Susan Freeman
Millennium Metallurgy, Ltd.

Arun M. Gokhale
Georgia Institute of Technology

Mark Hadfield
Bournemouth University

Crispin Hales
Triodyne Inc.

Larry D. Hanke
Materials Evaluation and Engineering, Inc.

Jeffrey A. Hawk
Albany Research Center

Thomas R. Jack
NOVA Research and Technology Center

Jeffrey Jansen
Stork Technimet, Inc.

L.M. Jarvis
Tenaxol Inc.

Kent Johnson
Engineering Systems Inc.

Mitchell Kaplan
EAD Aerospace, Inc.

Randy K. Kent
MDE Engineers Inc.

Matthew T. Kiser
Caterpillar Inc.

John Landes
University of Tennessee

Allan D. Lang

Iain Le May
Metallurgical Consulting

Roger Lewis
The University of Sheffield

Cameron Lonsdale
Standard Steel

Russell A. Lund

Charles R. Manning
Accident Reconstruction Analysis Incorporated

William McBrine
Altran Corporation

Robert McCabe
AMC

Steve McDanels
National Aeronautics and Space Administration

Dennis McGarry
FTI-SEA Consulting

Daryll W. McKinley
McSwain Engineering, Inc.

Richard H. McSwain
McSwain Engineering, Inc.

Brett A. Miller
Stork Technimet Corporation

Harry R. Millwater, Jr.
University of Texas at San Antonio

M. Narazaki
Utsunomiya University (Japan)

Howard Nelson

Dana E. Netherton
Athos Corporation

John G. Newman
Physical Electronics Inc.

Ronald J. Parrington
IMR Test Labs

Cheryl Pattin
Triodyne Inc.

Ray Pelaez
CorrTech Inc.

James Pineault
Proto Manufacturing Limited

Robert B. Pond, Jr.
M-Structures Inc.

Gordon Powell
The Ohio State University

Julian J. Raphael
Columbus McKinnon Corporation

Harold S. Reemsnyder
Fracture Technology Associates

Roger H. Richman
Daedalus Associates Inc.

Michel Rigaud
École Polytechnique (Montreal)

Ashok Saxena
Georgia Institute of Technology

James J. Scutti
Massachusetts Materials Research, Inc.

Tom Service
Altran Corporation

Shahram Sheybany
Pacific Metallurgical Company

David A. Shifler
Naval Surface Warfare Center

Roch J. Shipley
Packer Engineering Inc.

Sujeet Sinha
National Institute of Advanced Industrial Science and Technology

Charles O. Smith
Engineering Consultant

V.P. Swaminathan
Turbomet International

Aaron Tanzer
Siemens-Westinghouse

R. Bruce Thompson
Iowa State University

George E. Totten
G.E. Totten & Associates LLC

George F. Vander Voort
Buehler, Ltd.

James R. Varner
Alfred University

Frank W. Veit
Siemens Dematic Rapistans Systems Division

William R. Warke

Thomas C. Wenzel
Accident Reconstruction Analysis Incorporated

Bryan E. Wilde

Richard Wilson
Albany Research Center

Paul H. Wirsching
University of Arizona

Timothy A. Wolff
EAD Aerospace, Inc.

Contents

Publication title	**Product code**
ASM Handbook Volume 11: Failure Analysis and Prevention	**06072G**

ASM Handbookå§ž Volume 9 Metallography and Microstructures Prepared under the direction of the ASM International Handbook Committee. George F. Vander Voort, Volume Editor. Steven R. Lampman, Project Editor Bonnie R. Sanders, Manager of Production Gayle J. Anton, Editorial Assistant Carol Polakowski, Production Supervisor Jill Kinson, Production Editor Kathryn Muldoon, Production Assistant Scott D. Henry, Senior Manager, Product and Service Development William W. Scott, Jr., Director of Technical Publications. ASM Handbook, Volume 9: Metallography and Microstructures. G.F. Vander Voort, editor, p493â€“512. DOI: 10.1361/asmhba0003752.   Fig. 5 Extensive mechanical twinning was observed in. high-purity, electron-beam-melted zirconium af