

Contents

For a more detailed Table of Contents, see page x.

ASM Handbook®

Volume 8
Mechanical Testing and Evaluation

Prepared under the direction of the
ASM International Handbook Committee

Volume Editors
Howard Kuhn, Concurrent Technologies Corporation
Dana Medlin, The Timken Company

ASM International Staff
Steven R. Lampman, Project Editor
Bonnie R. Sanders, Manager of Production
Nancy Hrivnak and Carol Terman, Copy Editors
Kathleen S. Dragolich, Production Supervisor
Candace Mullet and Jill Kinson, Production Coordinators
Scott D. Henry, Assistant Director of Reference Publications
William W. Scott, Jr., Director of Technical Publications

Editorial Assistance
Erika Baxter
Kelly Ferjutz
Heather Lampman
Pat Morse
Mary Jane Riddlebaugh

The Materials
Information Society

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

First printing, October 2000

This book is a collective effort involving hundreds of technical specialists. It brings together a wealth of information from world-wide sources to help scientists, engineers, and technicians solve current and long-range problems.

Great care is taken in the compilation and production of this Volume, but it should be made clear that NO WARRANTIES, EXPRESS OR IMPLIED, INCLUDING, WITHOUT LIMITATION, WARRANTIES OF MERCHANTABILITY OR FITNESS FOR A PARTICULAR PURPOSE, ARE GIVEN IN CONNECTION WITH THIS PUBLICATION. Although this information is believed to be accurate by ASM, ASM cannot guarantee that favorable results will be obtained from the use of this publication alone. This publication is intended for use by persons having technical skill, at their sole discretion and risk. Since the conditions of product or material use are outside of ASM's control, ASM assumes no liability or obligation in connection with any use of this information. No claim of any kind, whether as to products or information in this publication, and whether or not based on negligence, shall be greater in amount than the purchase price of this product or publication in respect of which damages are claimed. THE REMEDY HEREBY PROVIDED SHALL BE THE EXCLUSIVE AND SOLE REMEDY OF BUYER, AND IN NO EVENT SHALL EITHER PARTY BE LIABLE FOR SPECIAL, INDIRECT OR CONSEQUENTIAL DAMAGES WHETHER OR NOT CAUSED BY OR RESULTING FROM THE NEGLIGENCE OF SUCH PARTY. As with any material, evaluation of the material under end-use conditions prior to specification is essential. Therefore, specific testing under actual conditions is recommended.

Nothing contained in this book shall be construed as a grant of any right of manufacture, sale, use, or reproduction, in connection with any method, process, apparatus, product, composition, or system, whether or not covered by letters patent, copyright, or trademark, and nothing contained in this book shall be construed as a defense against any alleged infringement of letters patent, copyright, or trademark, or as a defense against liability for such infringement.

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

Library of Congress Control Number: 00-131388

ASM International

ASM Handbook
Vols. 1–2 have title: Metals 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.7. Powder metal technologies and applications

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 0-87170-389-0

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

Printed in the United States of America

Foreword

The new edition of *ASM Handbook,* Volume 8, *Mechanical Testing and Evaluation* is a substantial update and revision of the previous volume. This latest edition of Volume 8 contains over 50 new articles, and the scope of coverage has been broadened to include the mechanical testing of alloys, plastics, ceramics, composites, and common engineering components such as fasteners, gears, bearings, adhesive joints, and welds. This new scope is also complemented by substantial updates and additions in the coverage of traditional quasi-static testing, hardness testing, surface testing, creep deformation, high strain rate testing, fracture toughness, and fatigue testing.

The efforts of many people are to be commended for creating this useful, comprehensive reference on mechanical testing. The ASM Handbook Committee, the editors, the authors, the reviewers, and ASM staff have collaborated to produce a book that meets high technical standards for the benefit of engineering communities everywhere. To all who contributed to the completion of this task, we extend our sincere thanks.

Ash Khare
President
ASM International

Michael J. DeHaemer
Managing Director
ASM International

ASM Handbook, Volume 8, Mechanical Testing and Evaluation (#06772G)

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 × 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, by 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 ASTM Standard E 380, 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 ASTM E 380; 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

At least three major trends have occurred since the last edition of Volume 8 in 1984. First, concurrent engineering is growing in importance in the industrial world, and mechanical testing plays a major role in concurrent engineering through the measurement of properties of product design, as well as for deformation processing. *ASM Handbook,* Volume 20, *Materials Selection and Design* (1997) reflects this focus in concurrent engineering and the broadening spectrum of involvement of materials engineers. Second, new methods of measurement have evolved such as strain measurement by vision systems and ultrasonic methods for measurement of elastic properties. This area will continue to grow as miniaturized sensors and computer vision technologies mature. Third, computer modeling capabilities, based on fundamental continuum principles and numerical methods, have entered the mainstream of everyday engineering. The validity of these computer models depends heavily on the availability of accurate material properties from mechanical testing.

Toward this end, this revision of *ASM Handbook,* Volume 8 is intended to provide up-to-date, practical information on mechanical testing for metals, plastics, ceramics, and composites. The first section, "Introduction to Mechanical Testing and Evaluation," covers the basics of mechanical behavior of engineering materials and general engineering aspects of mechanical testing including coverage on the accreditation of testing laboratories, mechanical tests in metalworking operations, and the general mechanical tests of plastics and ceramics. The next three sections are organized around the basic modes of loading of materials: tension, compression bending, shear, and contact loads. The first four modes (tension, compression, bending, and shear) are the basic simple loading types for determination of bulk properties of materials under quasi-static or dynamic conditions.

The third section, "Hardness Testing," describes the various methods for indentation testing, which is a relatively inexpensive test of great importance in manufacturing quality control and materials science. This section includes new coverage on instrumented (nano-indentation) hardness testing and the special issues of hardness testing of ceramics. Following the section on hardness testing, the fourth section, addresses the mechanical evaluation of surfaces in terms of adhesion and wear characteristics from point loading and contact loading. These methods, often in conjunction with hardness tests, are used to determine the response of surfaces and coatings to mechanical loads.

The next four sections cover mechanical testing under important dynamic conditions of slow strain rates (i.e., creep deformation and stress relaxation), high strain rate testing, dynamic fracture, and fatigue. These four sections cover the nuances of testing materials under the basic loading types but with the added dimension of time as a factor. Very long-term, slow rate of loading (or unloading) in creep and stress relaxation is a key factor in many high-temperature applications and the testing of viscoelastic materials. On the opposite end of the spectrum, high strain rate testing characterizes material response during high-speed deformation processes and dynamic loading of products. Fracture toughness and fatigue testing are the remaining two sections covering engineering dynamic properties. These sections include coverage on the complex effects of temperature and environmental degradation on crack growth under cyclic or sustained loads.

Finally, the last section focuses on mechanical testing of some common types of engineering components such as gears, bearings, welds, adhesive joints, and mechanical fasteners. A detailed article on residual stress measurements is included, as residual stress from manufacturing operations can be a key factor in some forms of mechanical performance such as stress corrosion cracking and fatigue life analysis. Coverage of fiber-reinforced composites is also included as a special product form with many special and unique testing and evaluation requirements.

In this extensive revision, the end result is over 50 new articles and an all-new Volume 8 of the *ASM Handbook* series. As before, the key purpose of this Handbook volume is to explain test set-up, common testing problems and solutions, and data interpretations so that reasonably knowledgeable, but inexperienced, engineers can understand the factors that influence proper implementation and interpretation. Easily obtainable and recognizable standards and research publications are referenced within each article, but every attempt is made to provide sufficient clarification so that inexperienced readers can understand the reasons and proper interpretation of published industrial test standards and research publications.

In this effort, we greatly appreciate the knowledgeable guidance and support of all the section editors in developing content requirements and author recommendations. This new content would not have been possible without their help: Peter Blau, Oak Ridge National Laboratory; James C. Earthman, University of California/Irvine; Brian Klotz, General Motors Corporation; Peter K. Liaw, University of Tennessee; Sia Nemat-Nasser, University of California, San Diego; Todd M. Osman, U.S. Steel Research; Gopal Revankar, Deere & Company; Robert Ritchie, University of California at Berkeley. Finally, we are all especially indebted to the volunteer spirit and devotion of all the authors, who have given us their time and effort in putting their expertise and knowledge on paper for the benefit of others. This work would not have been possible without them.

Howard Kuhn
Concurrent Technologies Corporation

Dana Medlin
The Timken Company

Officers and Trustees of ASM International (1997–1998)

Members of the ASM Handbook Committee (1999–2000)

Previous Chairs of the ASM Handbook Committee

Authors and Contributors

John Bailey
North Carolina State University

John Barsom
Barsom Consulting Limited

Peter Blau
Oak Ridge National Laboratory

Kenneth Budinski
Eastman Kodak Company

Vispi Bulsara
Cummins Engine Company

Leif Carlsson
Florida Atlantic University

Norm Carroll
Applied Test Systems

Srinivasan Chandrasekar
Purdue University

P. Dadras
Wright State University

K.L. DeVries
University of Utah

George Dieter
University of Maryland

James Earthman
University of California/Irvine

Horacio Espinosa
Northwestern University

Henry Fairman
MQS Inspection, Inc.

Thomas Farris
Purdue University

Andrew Fee
Consultant

William Gerberich
University of Minnesota

Jeffery Gibeling
University of California, Irvine

Amos Gilat
Ohio State University

Peter Gillis
University of Kentucky

William Glaeser
Battelle Memorial Institute

Blythe Gore
Northwestern University

George (Rusty) Gray III
Los Alamos National Laboratory

Amitava Guha
Brush Wellman Inc.

Gary Halford
NASA Glenn Research Center at Lewis Field

John Harding
Oxford University

Jeffrey Hawk
Albany Research Center

Jennifer Hay
Applied Nano Metrics Inc.

Robert Hayes
Metals Technology Inc.

K.-H. Herter
University of Stuttgart

John (Tim) M. Holt
Alpha Consultants and Engineering

Joel House
Air Force Research Laboratory

Roger Hurst
Institute for Advanced Materials
(The Netherlands)

Ian Hutchings
University of Cambridge

Michael Jenkins
University of Washington

Steve Johnson
Georgia Institute of Technology

Serope Kalpakjian
Illinois Institute of Technology

Y. Katz
University of Minnesota

Kevin M. Kit
University of Tennessee

Brian Klotz
The General Motors Corporation

Howard Kuhn
Concurrent Technologies Corporation

John Landes
University of Tennessee

Bradley Lerch
NASA Glenn Research Center at Lewis Field

Peter Liaw
University of Tennessee

John Magee
Carpenter Technology Corporation

Frank Mandigo
Olin Corporation

Michael McGaw
McGaw Technology, Inc.

Lothar Meyer
Technische Universität Chemnitz

James Miller
Oak Ridge National Laboratory

Farghalli A. Mohamed
University of California

William C. Mohr
Edison Welding Institute

Charles A. Moyer
The Timken Company (retired)

Yukitaka Murakami
Kyushu University

Sia Nemat-Nasser
University of California, San Diego

Vitali Nesterenko
University of California, San Diego

Todd M. Osman
U.S. Steel

F. Otremba
University of Stuttgart

T. Ozaki
Olin Brass Japan, Inc.

George M. Pharr
The University of Tennessee

Paul Phillips
The University of Tennessee

Martin Prager
Welding Research Council and
Materials Properties Council

Lisa Pruitt
University of California, Berkeley

George Quinn
National Institute of Standards and
Technology

J.H. Rantala
Institute for Advanced Materials
(The Netherlands)

Suran Rao
Applied Research Laboratories

W. Ren
Air Force Research Laboratory

Gopal Revankar
Deere & Company

Robert Ritchie
University of California, Berkeley

Roxanne Robinson
American Association for Laboratory Accreditation

E. Roos
University of Stuttgart

Clayton Ruud
Pennsylvania State University

Jonathan Salem
NASA Glenn Research Center at Lewis Field

P. Sandberg
Outokupa Copper

Ashok Saxena
Georgia Institute of Technology

Eugene Shapiro
Olin Corporation

Ralph S. Shoberg
R.S. Technologies Ltd.

M.E. Stevenson
The University of Alabama

Ghatu Suhash
Michigan Technological University

Ed Tobolski
Wilson Instruments

N. Tymiak
University of Minnesota

George Vander Voort
Buehler Ltd.

Howard Voorhees
Materials Technology Corporation

Robert Walsh
Florida State University

Robert Waterhouse
University of Nottingham

Mark Weaver
University of Alabama

Dale Wilson
The Johns Hopkins University

David Woodford
Materials Performance Analysis, Inc.

Dan Zhao
Johnson Controls, Inc.

Reviewers

Julie Bannantine
Consultant

Raymond Bayer
Tribology Consultant

Peter Blau
Oak Ridge National Laboratory

Toni Brugger
Carpenter Technology Corporation

Prabir Chaudhury
Concurrent Technologies Corporation

Richard Cook
National Casein of California

Dennis Damico
Lord Corporation Chemical Products Division

Craig Darragh
The Timken Company

Mahmoud Demeri
Ford Research Laboratories

Dez Demianczuk
LTV Steel

George Dieter
University of Maryland

James Earthman
University of California/Irvine

Kathy Faber
Northwestern University

Henry Fairman
MQS Inspection Inc.

Gerard Gary
Polytechnique Institute (France)

Thomas Gibbons
Consultant

William Glaeser
Battelle Memorial Institute

Jennifer Hay
Applied Nano Metrics Inc.

Robert Hayes
Metals Technology Inc.

David Heberling
Southwestern Ohio Steel

Kent Johnson
Engineering Systems Inc.

Brian Klotz
The General Motors Corporation

Howard Kuhn
Concurrent Technologies Corporation

Lonnie Kuntz
Mar-Test, Inc.

David Lambert
Air Force Research Laboratory

John Landes
University of Tennessee

Iain LeMay
Metallurgical Consulting Services

John Lewandowski
Case Western Reserve University

David Lewicki
NASA Glenn Research Center at Lewis Field

Alan Male
University of Kentucky

John Makinson
University of Nebraska, Lincoln

William Mankins
Metallurgical Services Inc.

Frank Marsh
Consultant

Dana Medlin
The Timken Company

Gary Miller
Allegheny Ludlum Corporation

Sia Nemat-Nasser
University of California, San Diego

Robert Neugebauer
Mar-Test, Inc.

Theodore Nicholas
Air Force Research Laboratory
Wright-Patterson Air Force Base

William Nix
Stanford University

Todd Osman
U.S. Steel

Philip Pearson
The Torrington Company

J. Michael Pereira
NASA Research Center at Lewis Field

Joy Ransom
Fatigue Technology, Inc.

Gopal Revankar
Deere & Company

Clare Rimnac
Case Western Reserve University

Earl Ruth
Tinius Olsen Testing Machine Company Inc.

Ghatu Subhash
Michigan Technological University

Yuki Sugimura
Harvard University

Eric Taleff
The University of Texas at Austin

Ed Tobolski
Wilson Instruments

George Vander Voort
Buehler Ltd.

Kenneth S. Vecchio
University of California, San Diego

Contents

Publication title	Product code
ASM Handbook, Volume 8, Mechanical Testing and Evaluation	#06772G