

ASM Handbook®

Volume 21 Composites

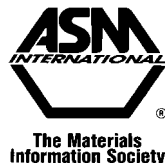
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Foreword

ASM International is proud to offer *Composites* as Volume 21 of the *ASM Handbook*. The nominal basis for this volume was the *Engineered Materials Handbook*, Volume 1, published in 1987. However, this new edition is, to a large degree, a brand new volume. New or greatly expanded coverage is provided, in particular, in the Sections on constituent materials, analysis and design, and processing. New sections have been added to address the important topics of maintenance, repair, and recycling. Coverage of polymer-matrix composites has been enhanced to address the latest materials advances and new application areas. Coverage of metal-matrix and ceramic-matrix composites has been revamped and greatly expanded to reflect the increasing industrial importance of these materials.

With the release of this new edition of the *Composites* volume, it seems like a natural transition for it to become part of the *ASM Handbook* series. The *Metals Handbook* series was renamed the *ASM Handbook* in the mid-1990s to reflect the increasingly interrelated nature of materials and manufacturing technologies. Since that time the *ASM Handbook* has incorporated increasing amounts of information about nonmetallic materials in each new and revised volume. ASM expects that other volumes in the *Engineered Materials Handbook* will become part of the *ASM Handbook* when they are revised.

Creating the new edition of this monumental reference work was a daunting task. We extend thanks and congratulations on behalf of ASM International to the Volume Chairs, Dan Miracle and Steve Donaldson, and the Volume's 13 Section Chairs for the outstanding job they have done in developing the outline for the revision and guiding its development. Our gratitude is also due to the over 300 international experts from industry, academia, and research who contributed as authors and reviewers to this edition. In addition, we express our appreciation to the ASM International editorial and production staff for their dedicated efforts in preparing this volume for publication.

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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 ($\text{kg} \times 10^3$) 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

It should be apparent with just a quick glance through this Volume that a great deal of technical progress has been made since the first edition was published in 1987 (as *Engineered Materials Handbook*, Volume 1). Much of the earlier promise of high performance organic-matrix composites (OMCs) has been fulfilled. These materials are now the preferred design solution for an expansive scope of applications. Earlier concerns related to high cost and marginal manufacturability have been satisfactorily addressed through high volume and innovative design and manufacturing, including extensive use of unitized design and construction. A clear example of the success in these areas is illustrated by the growing use of high-performance composites in the commodity applications of civil infrastructure. Nonetheless, cost and manufacturability continue to be areas of vigorous development and hold hope for significant future advancements, along with the development of composite materials with higher specific properties, higher operating temperatures, and improved supportability. One can expect to see broad advances in innovative structural concepts and certification methods in the future.

The progress in metal-matrix composites (MMCs) has been equally remarkable. Although only marginal coverage was warranted in the first edition, MMCs now represent a significant material option in the international marketplace. The world market for MMCs was over 2.5 million kg (5.5 million pounds) in 1999, and an annual growth rate of over 17% has been projected for the next several years. Significant applications are in service in the aeronautical, aerospace, ground transportation, thermal management/electronic packaging, and recreation industries. The ability to offer significant improvements in structural efficiency and to excel in several other functional areas, including thermal management and wear, and to utilize existing metalworking infrastructure have aided this progress. Continued future extension into both new and existing markets is expected.

While ceramic-matrix composite (CMC) technology is still largely centered in the research and development phase, significant advancements have been made. Some commercial applications now exist, and strategies for growing market insertion are being pursued. The traditional motivation of structural performance and environmental resistance at the highest application temperatures continue to provide incentive for development. Recent important research accomplishments provide growing optimism that significant aer propulsion structural applications will be fielded in the coming decade.

The primary objective of *ASM Handbook*, Volume 21, *Composites*

is to provide a comprehensive, practical, and reliable source of technical knowledge, engineering data, and supporting information for composite materials. Coverage of OMCs and MMCs is provided in a balanced fashion that reflects the maturity of each material class. Given the current status of CMC materials, less coverage is provided, but it, too, is focused in areas of current industrial importance. This Handbook is intended to be a resource volume for nonspecialists who are interested in gaining a practical working knowledge of the capabilities and applications of composite materials. Thus, coverage emphasizes well-qualified information for materials that can be produced in quantities and product forms of engineering significance. This Volume is not intended to be a presentation of fundamental research activities, although it certainly provides an important reference for scientists engaged in the development of new composite materials. The full range of information of importance to the practical technologist is provided in this Volume, including topics of constituent materials; engineering mechanics, design, and analysis; manufacturing processes; post-processing and assembly; quality control; testing and certification; properties and performance; product reliability, maintainability, and repair; failure analysis; recycling and disposal; and applications.

This new edition builds on the success of the version published as Volume 1 of the *Engineered Materials Handbook*. Information on OMCs has been updated to reflect advancements in this technology field, including improvements in low cost manufacturing technologies and significantly expanded applications in areas such as infrastructure. Progress in MMCs has been particularly dramatic since the previous edition, and new information on these materials provides an up-to-date comprehensive guide to MMC processing, properties, applications, and technology. CMCs also have entered service in limited applications since the previous edition, and the coverage of these materials reflects this progress. These three classes of composites are covered in each Section of the Volume as appropriate to provide a unified view of these engineered materials and to reduce redundancies in the previous edition.

We would like to offer our personal, heartfelt appreciation to the Section Chairpersons, article authors, reviewers, and ASM staff for sharing both their expertise and extensive efforts for this project.

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