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Volume 13B
Corrosion: Materials

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Foreword

Enhancing the life of structures and engineered materials, while protecting the environment and public safety, is one of the paramount technological challenges for our nation and the world. Corrosion-related problems span a wide spectrum of materials and systems that impact our daily lives, such as aging aircraft, high-rise structures, railroads, automobiles, ships, pipelines, and many others. According to a study conducted in 1998, the total direct and indirect cost of corrosion to the United States alone exceeds $550 billion per year. While major technological advances have been made during the last three decades, numerous new innovations need to be made in the coming years. ASM International is pleased to publish *ASM Handbook,* Volume 13B, *Corrosion: Materials,* the second book in a three-volume revision of the landmark 1987 *Metals Handbook,* 9th Edition, on corrosion. The information from the 1987 Volume has been revised, updated, and expanded to address the needs of the members of ASM International and the technical community for current and comprehensive information on the physical, chemical, and electrochemical reactions between specific materials and environments. Since the time the 1987 *Corrosion* volume was published, knowledge of materials and corrosion has grown, which aids the material selection process. Engineered systems have grown in complexity, however, making the effects of subtle changes in material performance more significant.

ASM International continues to be indebted to the Editors, Stephen D. Cramer and Bernard S. Covino, Jr., who had the vision and the drive to undertake the huge effort of updating and revising the 1987 *Corrosion* volume. *ASM Handbook,* Volume 13A, *Corrosion: Fundamentals, Testing, and Protection,* published in 2003, is the cornerstone of their effort. The project will be completed with the publication of *ASM Handbook,* Volume 13C, *Corrosion: Environments and Industries,* in 2006. The Editors have brought together experts from across the globe making this an international effort. Contributors to the corrosion Volumes represent Australia, Belgium, Canada, Crete, Finland, France, Germany, India, Italy, Japan, Korea, Mexico, Poland, South Africa, Sweden, Switzerland, and the United Kingdom, as well as the United States. The review, revisions, and technical oversight of the Editors have added greatly to this body of knowledge.

We thank the authors and reviewers of the 1987 *Corrosion* volume, which at the time was the largest, most comprehensive volume on a single topic ever published by ASM. This new edition builds upon that groundbreaking project. Thanks also go to the members of the ASM Handbook Committee for their oversight and involvement, and to the ASM editorial and production staff for their tireless efforts.

We are especially grateful to the over 120 authors and reviewers listed in the next several pages. Their willingness to invest their time and effort and to share their knowledge and experience by writing, rewriting, and reviewing articles has made this Handbook an outstanding source of information.

Bhakta B. Rath
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Stanley C. Theobald
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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

Corrosion, while silent and often subtle, is probably the most significant cause of degradation of society's structures. Over the past 100 years, efforts have been made to estimate the cost of corrosion to the economies of various countries. These efforts have been updated to 2004 in this Handbook, and extrapolated to the global economy to provide an estimate of the global cost of corrosion (Ref 1). With a 2004 global Gross Domestic Product (GDP) of about $50 trillion United States dollars (USD), the direct cost of corrosion was estimated to be $990 billion (USD) annually, or 2.0 percent of the world GDP (Ref 1). The direct cost is that experienced by owners and operators of manufactured equipment and systems and of other man-made objects (Ref 2). The indirect cost of corrosion, representing costs assumed by the end user and the overall economy (Ref 2), was estimated to be $940 billion (USD) annually (Ref 1). On this basis, the 2004 total cost of corrosion to the global economy was estimated to be about $1.9 trillion (USD) annually, or 3.8 percent of the world GDP. The largest contribution to this cost comes from the United States at 31 percent, with other major contributions being: Japan—6 percent, Russia—6 percent, Germany—5 percent, and the UK, Australia, and Belgium—1 percent.

ASM Handbook Volume 13B, *Corrosion: Materials,* is the second volume in a three-volume update, revision, and expansion of *Corrosion* published in 1987 as Volume 13 of the ninth edition *Metals Handbook*. The first volume—*ASM Handbook* Volume 13A, *Corrosion: Fundamentals, Testing, and Protection*—was published in 2003. Volume 13C, *Corrosion: Environments and Industries,* will be published in 2006. The purpose of these three volumes is to present the current state of knowledge of corrosion, efforts to mitigate corrosion's effects on society's structures and economies, and some perspective on future trends in corrosion prevention and mitigation. Metals remain the primary materials focus of the Handbook, but nonmetallic materials occupy a more prominent position, reflecting their wide and effective use to solve problems of corrosion and their frequent use with metals in complex engineering systems. Wet (or aqueous) corrosion remains the primary environmental focus, but dry (or gaseous) corrosion is also addressed, reflecting the increased use of elevated or high temperature operations in engineering systems, particularly energy-related systems where corrosion and oxidation are important considerations.

As with Volume 13A, Volume 13B recognizes the diverse range of materials, environments, and industries affected by corrosion, the global reach of corrosion practice, and the levels of technical activity and cooperation required to produce cost-effective, safe, and environmentally-sound solutions to materials problems in chemically aggressive environments. As we worked on this project, we marveled at the spread of corrosion technology into many engineering technologies and fields of human activity. This occurred because the pioneers of corrosion technology from the early to mid-20th century, and the organizations they helped create, were able to effectively communicate and disseminate their knowledge to an ever widening audience through educational, training, and outreach activities. One quarter of the articles in Volume 13B did not appear in the 1987 Handbook. Authors from eight countries contributed to Volume 13B. The references for each article are augmented by Selected References to provide access to a wealth of additional information on corrosion.

Volume 13B is organized into three major sections addressing the materials used in society's structures and their performance over time. These sections recognize that materials are chemicals and respond to the laws of chemistry and physics, that with sufficient knowledge corrosion is predictable, and therefore, within the constraints of design and operating conditions, corrosion can be minimized to provide economic, environmental, and safety benefits.

The first Section, "Corrosion of Ferrous Metals," examines the corrosion performance of wrought carbon steels, wrought low alloy steels, weathering steels, metallic-coated steels, organic-coated steels, cast irons, cast carbon and low alloy steels, wrought stainless steels, and cast stainless steels. These materials include a wide spectrum of end-use products utilizing steel's desirable characteristics of lightness, high strength and stiffness, adaptability, ease of prefabrication and mass production, dimensional stability, durability, abrasion resistance, uniform quality, noncombustibility, and ability to be recycled. In today's worldwide market, cost comes into play in the material selection process only after the user's functional requirements, particularly durability, are met. Expectations for low maintenance and long life, crucial for a favorable life cycle cost evaluation, require that long-term durability, including corrosion performance, can be substantiated through prior experience and test data.

The second Section, "Corrosion of Nonferrous Metals and Specialty Products," addresses the corrosion performance of metals and alloys made from aluminum, beryllium, cobalt, copper, hafnium, lead, magnesium, nickel, niobium, precious metals, tantalum, tin, titanium, uranium, zinc, zirconium, and specialty products including brazed and soldered joints, thermal spray coatings, electroplated hard chromium, clad metals, powder metallurgy materials, amorphous metals, intermetallics, carbides, and metal matrix composites. Numerous nonferrous alloys have extremely desirable physical and mechanical properties and have much higher resistance to corrosion and oxidation than steels and stainless steels. The most widely used nonferrous materials are those based on aluminum, copper, nickel, and titanium. Powder metallurgy materials, amorphous metals, intermetallics, cemented carbides, and metal matrix composites are defined less by their compositions than by their microstructures, which provide physical, mechanical, and corrosion and oxidation resistance unlike those of the traditionally processed metals and alloys. In most structures designed to resist corrosion, joints represent the greatest challenge. Coatings and claddings protect vulnerable substrate materials by resisting the impact of corrosive or oxidizing media or by acting as sacrificial anodes.

The third Section, "Environmental Performance of Nonmetallic Materials," addresses the performance of refractories, ceramics, concrete, protective coatings, rubber linings, elastomers, and thermosetting resins and resin matrix composites in aggressive environments. A significant number of engineering materials applications are fulfilled by nonmetallic materials. While nonmetallic materials are extensively used in engineering systems, they can degrade is with time, sometimes with catastrophic effect. The goal of this section is to indicate the chemical resistance of a variety of commonly used nonmetallic materials and provide further references for those seeking more in-depth information on their environmental performance. In this regard, testing for chemical and mechanical compatibility is usually warranted before nonmetallic materials are placed into a specific service.

The Handbook concludes with the estimate of the "Global Cost of Corrosion" noted at the beginning of this Preface and a "Gallery of Corrosion Damage." Using earlier cost studies as a basis, the 2004 total cost of corrosion to the global economy, including both direct and indirect costs, was estimated to be about $1.9 trillion (USD) annually, or 3.8 percent of the world GDP. The "Gallery of Corrosion Damage" contains color photographs of corrosion damage to complement the many black and white examples that accompany individual articles in the three volume series. The Gallery was assembled from photographs taken by experts in their practice of corrosion control and prevention in industrial environments. The photographs illustrate forms of corrosion and how they appear on inspection in specific environments, with a brief analysis of the corrosion problem and discussion of how the problem was corrected.

Supporting material at the back of the handbook includes a variety of useful information. A "Periodic Table of the Elements" provides fundamental information on the elements and gives their organization by group using three conventions: Chemical Abstract Service (CAS), International Union of Pure and Applied Chemistry (IUPAC)-1970, and IUPAC-1988. A concise description of "Crystal Structure" is given. "Density of Metals and Alloys" gives values for a wide range of metals and alloys. "Reference Electrodes" provides data on the commonly used reference electrodes and "Overpotential" distinguishes overpotential and overvoltage. The "Electrochemical Series" from the CRC Handbook is reproduced giving standard reduction potentials for a lengthy array of elements. A "Galvanic Series of Metals and Alloys in Seawater" shows materials by their potential with respect to the saturated calomel electrode (SCE) reference electrode. The "Compatibility Guide" serves as a reference to metal couples in various environments. A "Corrosion Rate Conversion" includes conversions in both nomograph and tabular form. The "Metric Conversion Guide" gives conversion factors for common units and includes SI prefixes. "Abbreviations and Symbols" provides a key to common acronyms, abbreviations, and symbols used in the Handbook.

Many individuals contributed to Volume 13B. In particular we wish to recognize the efforts of the following individuals who provided leadership in organizing subsections of the Handbook (listed in alphabetical order):

Chairperson	Subsection title
Rajan Bhaskaran	Global Cost of Corrosion
Arthur Cohen	Corrosion of Copper and Copper Alloys
Bernard Covino, Jr.	Corrosion of Specialty Products
Stephen Cramer	Corrosion of Carbon and Alloy Steels, Corrosion of Low Melting Metals and Alloys
Paul Crook	Corrosion of Cobalt and Cobalt-Base Alloys, Corrosion of Nickel-Base Alloys
Peter Elliott	Gallery of Corrosion Damage
John F. Grubb	Corrosion of Stainless Steels
Gil Kaufman	Corrosion of Aluminum and Aluminum Alloys
Barbara Shaw	Corrosion of Magnesium and Magnesium-Base Alloys
David C. Silverman	Environmental Performance of Non-Metallic Materials
Richard Sutherlin	Corrosion of Reactive and Refractory Metals and Alloys
Gregory Zhang	Corrosion of Zinc and Zinc Alloys

These knowledgeable and dedicated individuals generously devoted considerable time to the preparation of the Handbook. They were joined in this effort by more than 70 authors who contributed their expertise and creativity in a collaboration to write and revise the articles in the Handbook, and by the many reviewers of these articles. These volunteers built on the contributions of earlier Handbook authors and reviewers who provided the solid foundation on which the present Handbook rests.

For articles revised from the 1987 edition, the contribution of the previous author is acknowledged at the end of the article. This location in no way diminishes their contribution or our gratitude. Those authors responsible for the current revision are named after the title. The variation in the amount of revision is broad. The many completely new articles presented no challenge for attribution, but assigning fair credit for revised articles was more problematic. The choice of presenting authors' names without comment or with the qualifier "Revised by" is solely the responsibility of the ASM staff.

We thank ASM International and the ASM staff for the skilled support and valued expertise in the production of this Handbook. In particular, we thank Charles Moosbrugger, Gayle Anton, and Scott Henry for their encouragement, tactful diplomacy, and many helpful discussions. We are most grateful to the Albany Research Center, U.S. Department of Energy, for the support and flexibility in our assignments that enabled us to participate in this project. In particular, we thank Jeffrey A. Hawk and Cynthia A. Powell for their gracious and generous encouragement throughout the project.

Stephen D. Cramer
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