ASM Handbook, Volume 18, Friction, Lubrication, and Wear Technology
George E. Totten, editor

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Foreword

2016–2017 has been a time period in which ASM International has implemented its strategic plan for "The ASM Renewal." Key tenants of the renewal have been a focus on technical excellence, membership, and strategic collaborations. Pursuit of these has been guided by a fundamental belief that ASM provides maximum value to its members and society when working at the intersection of engineering/design, materials, and manufacturing. Further, ASM International is a society of members who have come together to do great things that cannot be done individually.

The origins of ASM can be traced to 1913 and the formation of the Steel Treaters Club in Detroit. Since that time, ASM has grown and now embraces a wide diversity of materials and processing technologies. However, the purpose of ASM, as stated in Section 4 of the ASM Constitution, is "ASM is formed for the exclusive purpose of advancing and disseminating scientific, engineering, and technical knowledge, particularly with respect to the manufacture, processing, characterization, selection, understanding, use, and life-cycle of engineered materials, through education, research, and the compilation and dissemination of information to serve technical and professional needs and interests and to benefit the general public."

The publication of *ASM Handbook*, Volume 18, *Friction, Lubrication, and Wear Technology* is the embodiment of the core values and beliefs that our Society holds dear. Volume Editor George Totten, seven Division Editors, and over 200 authors and reviewers worked to revise *ASM Handbook*, Volume 18, *Friction, Lubrication, and Wear Technology* from its original 1992 edition. Volume 18 is a resource for engineers and technical personnel who are looking to find practical solutions to real-world tribological problems.

In quoting Peter Blau, Volume Editor of the first edition, the content is to help in "selecting the right tool for the right job." Coverage includes the fundamental physical principles and materials properties that are the basis of understanding and solving tribological problems.

Additionally, as in every *ASM Handbook* volume, Volume 18 provides readers with reference information in the form of charts, graphs, tables, and key equations to help solve specific problems. In addition to basic concepts, methods of lab testing and analysis, materials selection, and field diagnosis and monitoring of friction and wear also are covered in Volume 18. The key focus of the Volume is improved materials performance through informed materials selection, lubrication use, and employment of surface treatments and coatings.

Volume 18 embodies the most comprehensive, up-to-date, and competitive tribological reference information available in the world today. With this valuable reference publication newly revised, ASM International is the best option for materials scientists, engineers, and technicians focused on solving the most pressing tribological issues. It is also emblematic of The ASM Renewal.

William E. Frazier "Pilgrim"
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George E. Totten, editor

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Preface to the First Edition

Friction, lubrication, and wear (FL&W) technology impacts many aspects of daily life, from the wear of one's teeth to the design of intricate, high-speed bearings for the space shuttle. Nearly everyone encounters an FL&W problem from time to time. Sometimes the solution to the problem is simple and obvious—disassembling, cleaning, and relubricating a door hinge, for example. Sometimes, however, the problem itself is difficult to define, the contact conditions in the system difficult to characterize, and the solution elusive.

Approaches to problem-solving in the multidisciplinary field of tribology (that is, the science and technology of FL&W) often present a wide range of options and can include such diverse fields as mechanical design, lubrication, contact mechanics, fluid dynamics, surface chemistry, solid-state physics, and materials science and engineering. Practical experience is a very important resource for solving many types of FL&W problems, often replacing the application of rigorous tribology theory or engineering equations. Selecting "the right tool for the right job" was an inherent principle in planning the contents of this Volume.

It is unrealistic to expect that specific answers to all conceivable FL&W problems will be found herein. Rather, this Handbook has been designed as a resource for basic concepts, methods of laboratory testing and analysis, materials selection, and field diagnosis of tribology problems. As Volume Chairman, I asked the Handbook contributors to keep in mind the question: "What information would I like to have on my desk to help me with friction, lubrication, or wear problems?" More than 100 specialized experts have risen to this challenge, and a wealth of useful information resides in this book.

The sections on solid friction, lubricants and lubrication, and wear and surface damage contain basic, tutorial information that helps introduce the materials-oriented professional to established concepts in tribology. The Handbook is also intended for use by individuals with a background in mechanics or lubricant chemistry and little knowledge of materials. For example, some readers may not be familiar with the measurement and units of viscosity or the regimes of lubrication, and others may not know the difference between brass and bronze. The "Glossary of Terms" helps to clarify the use of terminology and jargon in this multidisciplinary area. The discerning reader will find the language of FL&W technology to be somewhat imprecise; consequently, careful attention to context is advised when reading the different articles in the Volume.

The articles devoted to various laboratory techniques for conducting FL&W analyses offer a choice of tools to the reader for measuring wear accurately, using these measurements to compute wear rates, understanding and interpreting the results of surface imaging techniques, and designing experiments such that the important test variables have been isolated and controlled. Because many tribosystems contain a host of thermal, mechanical, materials, and chemical influences, structured approaches to analyzing complex tribosystems have also been provided.

The articles devoted to specific friction- or wear-critical components are intended to exemplify design and materials selection strategies. A number of typical tribological components or classes of components are described, but it was obviously impossible to include all the types of moving mechanical assemblies that may experience FL&W problems. Enough diversity is provided, however, to give the reader a solid basis for attacking other types of problems. The earlier sections dealing with the basic principles of FL&W science and technology should also be useful in this regard.

Later sections of the Handbook address specific types of materials and how they react in friction and wear situations. Irons, alloy steels, Babbitts, and copper alloys (brasses and bronzes) probably account for the major tonnage of tribological materials in use today, but there are technologically important situations where these workhorse materials may not be appropriate. Readers with tribomaterials problems may find the sections on other materials choices, such as carbon-graphites, ceramics, polymers, and intermetallic compounds, helpful in providing alternate materials-based solutions. In addition, the section on surface treatments and modifications should be valuable for attacking specialized friction and wear problems. Again, the point is to find the right material for the right job.

This Volume marks the first time that ASM International has compiled a handbook of FL&W technology. The tribology research and development community is quite small compared with other disciplines, and the experts who agreed to author articles for this Volume are extremely busy people. I am delighted that such an outstanding group of authors rallied to the cause, one that ASM and the entire tribology community can take pride in. I wish to thank all the contributors heartily for their much-appreciated dedication to this complex and important project in applied materials technology.

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Preface to the Second Edition

Tribology is an interdisciplinary study of material properties, including design, friction, wear, and lubrication of interacting surfaces in relative motion. Friction is the resistance of materials to relative motion, and wear is the loss of material due to that motion. Lubrication refers to the use of a fluid or solid to minimize friction and wear. From this definition, it is evident that tribological properties are fundamental to the wide-ranging materials, processes, and technologies of interest to ASM International. This recognition led to the development of the first edition of *ASM Handbook*, Volume 18, *Friction, Lubrication, and Wear Technology*.

The first edition of Volume 18, which was published in 1992, addressed the tribological properties of materials, including solid friction, lubricants and lubrication, wear, laboratory characterization techniques, systematic diagnosis of friction and wear tests, friction and wear of components, materials for friction and wear applications, and surface treatments and coatings for friction and wear control. Although this comprehensive treatment has been an invaluable resource for 25 years, there have been numerous material and technology developments that were not reflected in the topical coverage of the first edition. In view of the time that has elapsed since the publication of the first edition and the necessity for updating the coverage, a decision was made to develop the second edition.

The second edition of *ASM Handbook*, Volume 18, *Friction, Lubrication, and Wear Technology* has undergone a significant expansion and revision of coverage by a new group of global experts. There has been some reorganization of the topical coverage to better accommodate new material for inclusion. The comprehensive, revised, and peer-reviewed coverage of the second edition was targeted for a broad audience, including researchers, engineers, technicians, students, and quality-control personnel.

This new comprehensive reference would not have been possible without the vital contributions of our dedicated and conscientious editors, article contributors, and staff. My most sincere thanks and appreciation to all.

Dr. George E. Totten, FASM
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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 (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, 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.

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