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ASM Handbook®

Volume 6A
Welding Fundamentals and Processes

Prepared under the direction of the
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Foreword

From the efforts of volunteer editors, authors, and reviewers, this Volume 6A of the *ASM Handbook* series, provides updated and expanded coverage on the fundamentals and processes of welding technology, research, modeling and simulation. Welding and allied joining technologies are instrumental in the modern use of materials, and the many volunteers should be proud in this work to serve engineers, students, technicians, researchers, and others with authoritative, reliable reference information on welding fundamentals and processes.

Coverage of joining technologies continues to grow in the *ASM Handbook* series, and this Volume is the first of several Volumes devoted to the many new developments of materials joining. In this Volume, new coverage reflects the continued growth of solid-state welding processes and the expanded use of computer modeling in the simulation of welding processes. Procedure development, quality control, and process improvements are also emphasized for arc, resistance, and directed-energy beam welding.

ASM Handbooks are a cornerstone of ASM International, and this effort could not have been accomplished without the dedicated efforts of many volunteers. Our thanks are extended to the editors, listed on the title page, and the authors and reviewers given in the List of Contributors. We are grateful for the contribution of their time and expertise.

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Preface

The ASM Handbook Volume 6A, *Welding Fundamentals & Processes*, represents the first of at least two volumes to be published on aspects of welding and joining. As indicated in the title, Volume 6A focuses on fundamental aspects of welding, and on the many welding processes. Volume 6B, planned for future publication, will concentrate on weldability and behavior of a range of alloys and materials.

As with the last edition of this Volume, the Volume Editors recognized that the researchers, engineers, technicians and students that will use this handbook have different needs with regard to their level of understanding. Accordingly, the sections of this handbook fall into two major categories. The sections on fundamentals provide in-depth background on the scientific principles associated with welding, while the sections on the various welding processes take a more practical approach. The Volume Editors have also tried to present a comprehensive reference that can be of use to the diverse welding community.

All sections of the handbook have been reviewed to be sure that they reflect the current status of the technology. Many sections have been expanded, such as the sections on fundamentals, high-energy density, solid-state welding and especially weld modeling. New processes and process variations developed since the last printing of this Volume have been incorporated, including friction stir welding, magnetic pulse welding, hybrid processes, direct metal deposition, penetration enhancing fluxes and ultrasonic additive manufacturing. A section on safe practices has also been added.

We wish to thank our many colleagues who served as section editors and authors of the individual articles. This handbook would not have been possible without their efforts.

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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 $\times$ 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.

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