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Volume 14A
Metalworking: Bulk Forming

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Metalworking is one of the oldest and the most important of manufacturing technologies. Emerging from prehistoric times and progressing thru rapid advances during the Industrial Revolution, when large-scale steelmaking and metalworking operations became widespread. The scientific understanding of metallurgy and metalworking continued well into the 20th century, although in many instances the cost-effective manufacturing of parts still required the process of trial-and-error experimentation due to the complex material, mechanical, and thermal conditions of metalworking operations such as forging, rolling, and other thermomechanical processes.

Today, with the competitive demands of a global economy, the technologies of metalworking operations are being transformed in several ways. First and foremost, computer-aided design and manufacturing systems are becoming indispensable tools in all facets of metalworking. Computer simulations not only reduce or preclude the need for trial-and-error engineering of tooling and process conditions, but computer-based modeling also provides a tool for process optimization. Any industry must continuously evaluate the costs of competitive materials and the operations necessary for converting each material into cost-effective finished products. Manufacturing economy with no sacrifice in quality is paramount, and modern statistical and computer-based process design and control techniques are more important than ever. This book serves as an invaluable introduction to this rapidly evolved technology, and also provides a strong foundation with regard to more standard, well-established metalworking operations, as covered in this volume and Volume 14 of the 9th Edition Metals Handbook series.

Volume 14A of the ASM Handbook series is the first of two volumes covering the distinct processes and industries of bulk working and sheet forming. It covers bulk forming methods (such as forging, extrusion, drawing, and rolling), where three-dimensional deformation produces a new shape with significant change in the cross-section or thickness of a material. In contrast, Volume 14B covers the technology of the stamping and sheet-forming industry, where flat product is shaped into a new form without a significant change in the cross-sectional thickness. These two general categories of metalworking methods are distinct, and a two-volume set also allows for more content in comparison to the Volume 14 of the 9th Edition Metals Handbook, which covered both bulk forming and sheet forming technologies in one volume.

A successful Handbook is the culmination of the time and efforts of many world renowned contributors. To those individuals listed in the next several pages, we extend our sincere thanks. The Society is especially indebted to Dr. S.L. Semiatin for his tireless efforts in organizing and editing this volume. Finally, we are grateful for the support and guidance provided by the ASM Handbook Committee and the skill of an experienced editorial staff. As a result of these combined efforts, the tradition of excellence associated with the ASM Handbook continues.

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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×10³) 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/cm³ rather than kg/m³ 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

In the approximately 20 years since the 1988 publication of Volume 14, *Forming and Forging*, of the 9th Edition *Metals Handbook* series (renamed the *ASM Handbook* series in 1991), metalworking practice has seen a number of notable advances with regard to development of:

- New processes that include a number of novel techniques such as advanced roll forming methods, equal-channel angular extrusion, and incremental forging.
- Processes for new materials such as structural-intermetallic alloys and discontinuously-reinforced metal-matrix composites (MMCs) including dramatic approaches for the bulk forming of aluminate-based intermetallic materials and the utilization of commercial scale bulk forming for aluminum-alloy MMCs and, to a lesser extent, titanium-alloy MMCs.
- Improved microstructural control via specialized thermomechanical processing (TMP) of ferrous and nonferrous alloys with recent advances that include: TMP of ferrous alloys to produce carbide-free steels with bainitic microstructures and TMP of nickel-base superalloys to improve damage tolerance or creep resistance in service by techniques that produce a uniform intermediate grain size (ASTM ~6) or a graded microstructure.
- Advanced tools for predicting microstructure evolution based on phenomenological models (predicting, for example, the evolution of recrystallized volume fraction and recrystallized grain size that evolve during hot deformation) and mechanistic models that incorporate deterministic and statistical aspects to varying degrees and seek to quantify the specific mechanism underlying microstructure changes.
- Advanced tools for predicting texture evolution based on models for the prediction of either deformation textures or recrystallization/transformation textures.
- Advanced modeling and optimization techniques using powerful and inexpensive computer hardware and software that have resulted in a revolution in the design of bulk-forming processes.

These developments are briefly described in the article *Introduction to Bulk-Forming Processes* with more detailed articles covering each of these new developments. This edition also includes a new section *Forging Design* with detailed forging examples from past work published in an *ASM Forging Design* Handbook.

In addition, content from the 1988 edition has been split into a two-volume set. This volume focuses on bulk-working operations that include primary operations, in which cast products or consolidated powder billets are worked into mill shapes (such as bar, plate, tube, sheet, wire), and secondary operations in which mill products are further formed into finished products by hot forging, cold forging, drawing, extrusion, etc. The companion Volume 14B focuses on sheet forming, which has several characteristics that distinguish it from bulk working; for example, sheet formability includes different criteria such as springback and the resistance of a sheet material to thinning. In addition, sheet-forming operations typically involve large changes in shape (e.g., cup forming from a flat blank) without a significant change in the sheet thickness, whereas bulk-forming operations typically involve large changes in cross-sectional area (e.g., round bar extrusion or flat rolling) and may be accompanied by large changes in shape (e.g., impression die forging or shape rolling).

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