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Volume 3
Alloy Phase Diagrams

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Foreword

Alloy phase diagrams are used by metallurgists, materials engineers, and materials scientists to develop new alloys for specific applications; fabricate these alloys into useful configurations; design and control heat treatment procedures for alloys that will produce the required mechanical, physical, and chemical properties; and solve problems that arise with the performance of alloys in commercial applications.

ASM International has a proud history in the field of phase diagrams, including the ASM/NIST Data Program for Alloy Phase Diagrams and the resultant Phase Diagram Monograph Series; the Alloy Phase Diagram International Commission (APDIC) formed in partnership with other programs throughout the world; the online ASM Alloy Phase Diagram Database; the *Journal of Phase Equilibria and Diffusion*; and reference books including *Binary Alloy Phase Diagrams,* Second Edition; *Handbook of Ternary Alloy Phase Diagrams*; *Desk Handbook: Phase Diagrams for Binary Alloys*; and *Phase Diagrams of Dilute Binary Alloys*.

In the last 20 years, the phase diagram community has benefitted from marked improvements in experimental techniques, allowing for more accurate results. Even more importantly, computer modeling calculation methods have become more refined and reliable, to the point of augmenting or even replacing experimental results. Phase equilibria results that previously could not be determined practically, now can be found by these new calculation methods. This necessitated revisions of many previously accepted phase diagrams, prompting ASM to revise *ASM Handbook,* Volume 3, *Alloy Phase Diagrams,* first published in 1992.

Hiroaki Okamoto, Ph.D., Professor Emeritus of Asahi University, an editor of ASM International's *Journal of Phase Equilibria and Diffusion* and senior technical editor of the original Volume 3, led the effort to revise the Volume. Dr. Okamoto knew the 1992 edition could be improved upon significantly, because of his experience in recent years reviewing the literature and finding incorrectly drawn binary diagrams, based on thermodynamic arguments. Dr. Okamoto's decades of experience and his recent role as editor of ASM International's *Desk Handbook: Phase Diagrams for Binary Alloys*, Second Edition, prepared him for the laborious redrawing and updating of numerous binary and ternary diagrams for this new Volume. Dr. Okamoto, who has been involved with ASM publications for more than 35 years, was the perfect choice for the job, as he has studied, evaluated, and edited more diagrams than any other person alive today.

Mark E. Schlesinger, P.E., Professor of Metallurgical Engineering at Missouri University of Science and Technology, and an associate editor of the *Journal of Phase Equilibria and Diffusion*, contributed his expertise to this Volume by first selecting and then reviewing for accuracy and completeness the ternary diagrams. Erik M. Mueller, Ph.D., P.E., Materials Research Engineer at the National Transportation Safety Board, and a member of the ASM Handbook Committee, provided critical technical input in his review of the numerous introductory articles that now comprise Section 1 of the new edition.

Dr. Okamoto, or Hiro, as he is known to his colleagues, called upon two phase diagram subject matter experts—Dr. Hiroshi Ohtani, Professor at the Institute of Multidisciplinary Research for Advanced Materials at Tohoku University and Vice Chairman of the Japanese Committee for Alloy Phase Diagrams; and Dr. Seiji Miura, Professor in the Division of Materials Science and Engineering at Hokkaido University and Member of the Japanese Committee for Alloy Phase Diagrams—to review the binary diagrams. This Volume is enriched by their expertise.

ASM Handbook, Volume 3, *Alloy Phase Diagrams*, was prepared under the direction of the ASM Handbook Committee and the ASM Alloy Phase Diagram Committee, both of which confirmed the Volume should use the weight percent scale, rather than the atomic percent scale, to express alloy composition because most engineers still use weight percent to represent component concentration. This decision demonstrates ASM's continuing commitment to its members and its responsiveness to the phase equilibria community.

ASM International is grateful for the hard work and dedication of its Volume Editors, Hiroaki Okamoto, Mark E. Schlesinger, and Erik M. Mueller, and peer reviewers, Hiroshi Ohtani and Seiji Miura, who gave of their extensive expertise and time to make the Volume 3 revision a noteworthy addition to the *ASM Handbook* series.

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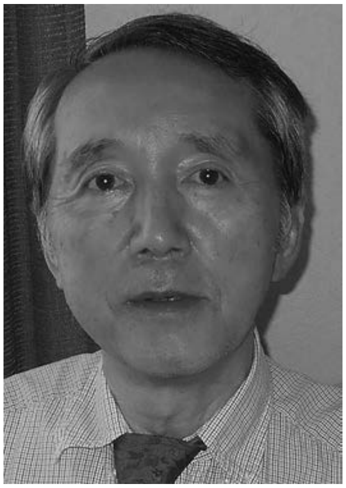
Preface



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More than two decades have passed since the previous edition of *ASM Handbook*, Volume 3, *Alloy Phase Diagrams* was published in 1992. During that time, improvements in experimental techniques and materials quality have increased the accuracy of experimental results, allowing better resolution of 'fine details' and filling the remaining gaps of existing systems and resolution of phase fields for phases of marginal stability. An even more significant advance is the increased sophistication and reliability of computer modeling techniques for phase diagram calculations. 'Optimizations' of binary, ternary, and higher-order systems are now commonplace, and the results are considered sufficiently trustworthy to compliment or even act as substitutes for experimentally determined data. These new calculation techniques can determine phase equilibria that could not be determined experimentally in a practical manner. The result has been numerous revisions of previously accepted phase diagrams, and predicted phase diagrams for newly assessed systems. The more recent advent of phase diagram calculations based on first principles may turn out to be the next revolution in the field.

In revising Volume 3, the decision was made to provide a better explanation of phase diagrams and their significance. This was done primarily by including several chapters of F.C. Campbell's *Phase Diagrams: Understanding the Basics* (ASM International, Materials Park, OH, 2012). The added material on ternary phase diagrams is of particular importance. Other explanatory material from the previous edition has been retained.

In displaying phase diagrams for this edition, it was again necessary to answer the question of whether to use atomic percent (or mole percent) scales to represent component concentration—nearly all phase diagrams currently published use atomic percent. However, most engineers still use weight percent to express alloy composition, and ASM International is at heart an organization dedicated to serving its membership. As a result, all the diagrams reproduced here use a weight percent scale. This required extensive redrawing of numerous published diagrams.

The binary section of the 1992 edition of the *ASM Handbook* was constructed by its editors by selecting 1053 phase diagrams from 2159 phase diagrams collected in *Binary Alloy Phase Diagrams, Second Edition by* editors T.B. Massalski, H. Okamoto, P.R. Subramanian, and L. Kacprzak, ASM International, Materials Park, OH, 1990. Most of these systems have been retained in this new edition, with the exception of 30 systems based on Eu, Np, and Os, which have found little practical application. A few others have been added, based on frequency of citation in the ASM Alloy Phase Diagram Database (P. Villars, editor-in-chief; H. Okamoto and K. Cenzual, section editors, ASM International, Materials Park, OH, 2006). ASM International since 1992 has published two collections of binary phase diagrams (H. Okamoto, *Desk Handbook: Phase Diagrams for Binary Alloys*, ASM International, Materials Park, OH, 2000; H. Okamoto, *Desk Handbook: Phase Diagrams for Binary Alloys (2nd Ed.)*, ASM International, Materials Park, OH, 2010). The revised diagrams produced for these collections are a significant portion of the total 1095 binary diagrams in this Volume.

The number of ternary systems (115) and ternary diagrams (406) in this Volume is a considerable expansion over the number published in the 1992 edition. The choice of new systems is again based primarily on citation frequency from the ASM Alloy Phase Diagram Database. While some of these systems have been extensively investigated, in several cases the age and scarcity of the available information compared poorly with the level of interest, suggesting a new way of prioritizing future ternary-system research!

We are indebted to two colleagues and subject matter experts, Dr. Hiroshi Ohtani, Tohoku University; and Dr. Seiji Miura, Hokkaido University; who graciously agreed to review page proofs of the Volume's binary phase diagrams.

ASM International staff who deserve thanks are Amy Nolan, Content Developer; Vicki Burt, Content Developer; Steve Lampman, Senior Content Developer; Karen Marken, Senior Managing Editor; Patty Conti, Production Coordinator; Diane Whitelaw, Production Coordinator; Kate Fornadel, Senior Production Coordinator; Madrid Tramble, Manager of Production; and Scott Henry, Director, Content and Knowledge-Based Solutions.

As always, reader feedback on the phase diagram selections and other material presented in this Volume will be valuable the next time a revised edition is produced. We hope the readers of this edition will gain a better understanding of phase diagram construction and alloy system interactions, while having a valuable resource available to aid in their research and engineering pursuits.

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 Volume 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 may 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 Volume 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 Volume. 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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Contents