ASM Handbook®

Volume 4C
Induction Heating and Heat Treatment

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Foreword

Heating and heat treatment by electromagnetic induction is a long-standing area of major interest of Heat Treating Society members, engineers, and manufacturers. From its initial applications in the latter half of the 19th Century for melting, induction heating technology continues to grow in applications that seem limited only by physics and our imaginations. The breadth and depth of thermal processing by electromagnetic induction technology are certainly deserving of a dedicated Volume to the *ASM Handbook*.

As such, this Volume marks the important milestone of an *ASM Handbook* devoted to practical and comprehensive coverage on many aspects of induction heating and heat treatment. *ASM Handbook*, Volume 4C, *Induction Heating and Heat Treatment*, also is a fitting expansion of handbook coverage on heat treatment. Given the roots of ASM International from its origin as the Steel Treaters Club in Detroit, heat treatment is a core constituency of ASM International and the Heat Treating Society (An Affiliate Society of ASM International).

This publication would not have been possible without the dedication and commitment by many volunteers around the globe and within the membership of ASM International and the Heat Treating Society. We are enormously grateful to them and their families for their devoted time and effort. We also are especially indebted to Valery Rudnev and George E. Totten as Volume Editors. This publication, quite simply, would have never occurred without them.

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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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Preface

This new *ASM Handbook*, Volume 4C, *Induction Heating and Heat Treatment*, is an important expansion of the *ASM Handbook* on heat treating by going beyond the focus on furnace heat treating in the previous *ASM Handbook*, Volume 4, *Heat Treating*. Heating by electromagnetic induction is a topic of major technological significance that continues to grow at accelerated rates in a variety of thermal applications such as hardening, tempering, stress relieving, brazing, soldering, melting, as well as preheating ferrous and nonferrous metallic alloys prior to warm and hot working. As such, this *ASM Handbook* Volume reflects an ambitious undertaking to compile an all-new, comprehensive resource on induction thermal processes in the twenty-first century.

Continuing in the tradition of the *ASM Handbook* series, this Volume provides a unique combination of practical knowledge grasping ready-to-use diagrams, technical procedures, guidelines, and good practices with advanced theoretical knowledge emphasizing *specifics* of induction processes compared to alternative technologies. Beginning with reviewing electrical, electromagnetic, heat transfer and material science fundamentals related to induction heating, along with coverage critical facets associated with this technology such as:

- Nonequilibrium nature of phase transformation and other metallurgical subtleties related to the specifics of induction hardening, tempering, stress relieving, heating prior to hot working and melting.
- Induction hardening of critical components, including gears, axle shafts, camshafts, crankshafts, and other components used in automotive and off-road machinery, aeronautic and aerospace engineering, farming, appliance, oil and gas industries.
- Review of ASTM and SAE standards and guidelines in proper measuring of hardness case depth and heat affected zone. Pattern specification as well as issues and complications related to different hardness measuring techniques. Destructive and nondestructive testing.
- Selection of critical process parameters and inductor styles, heat pattern control, the use of magnetic flux concentrators, quench design subtleties as well as a review and explanation of common misconceptions and erroneous assumptions.
- Formation of residual and transient stresses and their impact on a performance of heat treated components.
- Temperature requirements for heating carbon steels, alloy steels, super alloys, titanium, aluminum and copper alloys and other materials prior to hot and warm working. Novel technological developments in heating billets, bars, tubes, rods and other metallic workpieces.
- Optimization procedures and strategies in obtaining optimal process control algorithms based on various technological criteria, real-life constrains and cost functions (e.g., maximizing throughput and temperature uniformity, energy effectiveness, minimizing required shop floor space and metal loss, etc.). Principles of multiobjective optimization of induction heating devices.
- Failure analysis of induction heat treated components and comprehensive review of defects and abnormal characteristics.
- Good practices in designing and fabricating long-lasting induction coils and ways to avoid their premature failures.
- Special applications of electromagnetic induction, including melting glasses and oxides, optical fiber draw, nanoparticle heating and hyperthermia applications.
- Design principles and operation specifics of transistorized and thyristorized power supplies for induction heating needs.

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- Modern computer modeling and specifics of simulation of induction thermal processes.

This Volume also contains numerous case studies that illustrate the challenges and solutions in obtaining required thermal conditions with a workpiece. Practitioners, students, engineers, and scientists are always curious to find simple solutions for typical induction heating problems that they encounter every day. This book provides them with the knowledge to clearly understand the various interrelated physical phenomena that might be responsible for what is happening in real-life.

An appreciable amount of material is devoted to practical aspects, including review of standard and customized induction equipment. Special attention is paid to describing quality assurance, process monitoring, maintenance and safety procedures, energy and environmental aspects, including control of magnetic field exposure and review of international standards and regulations. Numerous articles, conference proceedings, and various technical books on induction heating and heat treating have been published by ASM International over the years, but much of the content in this Volume has never been published before.

The preparation of this tome was a tremendous task. Being editors, we are deeply indebted to all authors for their support, contribution and devotion; without them the project of this magnitude would not have been possible. Special thanks to Steve Lampman and the ASM staff. On many occasions, authors expressed to us their sincere gratitude for highly professional editing work and unending patience of ASM staff who are vital members of the team.

Very special thanks are given to our families and families of all contributors; this project would never have been completed without their sacrifices, understanding and support.

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