

ASM Handbook®

Volume 4C Induction Heating and Heat Treatment

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**Heat Treating
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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 Treating 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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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.

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 ($\text{kg} \times 10^3$) 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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Contents

Fundamentals	1	Residual Stresses in Induction Hardened Steels	
History and Applications	3	<i>Janez Grum</i>	103
History	3	Introduction	103
Applications of Induction Heating	4	General Features of Induction Hardening	103
Advantages of Induction Heating	4	Residual Stresses	105
Principles of Induction Heating		Residual Stresses Due to Quenching	108
<i>Sergio Lupi and Valery Rudnev</i>	6	Residual Stress Profiles	110
Heat Transfer Phenomena	6	Effects on Fatigue Strength	114
Direct Current and Alternating Current Circuits		Effects of Induction Hardening on Fatigue Strength and	
and Basic Electric Laws	14	Residual Stresses	118
Basic Concepts of the Theory of		Induction in Hybrid Processes	124
Electromagnetic Fields	16	Tempering of Induction Hardened Steels	
Electromagnetic and Thermal Properties of Materials		<i>Valery Rudnev, Gregory A. Fett and S. Lee Semiatin</i>	130
<i>Sergio Lupi and Valery Rudnev</i>	28	Tempering of Hardened Steel	130
Estimation of the Basic Induction Process Parameters		Specifics of Induction Heating Process	134
<i>Sergio Lupi and Valery Rudnev</i>	36	Self-Tempering	136
Workpiece Power Estimation for Through Heating		Induction Tempering Methods	137
Applications	36	Process Parameters for Induction Tempering	139
Coil Efficiency	36	Selection of Tempering Temperatures and Time	139
Frequency Selection	38	Effect of Process Variables	145
Conclusion	40	Good Practice in Induction Tempering	149
		Properties of Tempered Components	151
		Final Remarks	156
Induction Heat Treating	43	Induction Case Hardening of Axle Shafts	
Metallurgy of Induction Hardening of Steel		<i>Gregory A. Fett</i>	160
<i>David K. Matlock</i>	45	Introduction	160
Introduction	45	Axle Shafts	160
Steel Heat Treating Basics	45	Properties of Induction-Hardened Axle Shafts	162
Steel Heat Treatment by Induction Processing	50	Operations after Induction Hardening	170
Steel Alloys for Induction Processing	55	Induction Hardening of Crankshafts and Camshafts	
Principles of Induction Hardening and Inspection		<i>Gary Doyon, Valery Rudnev, and John Maher</i>	173
<i>Valery Rudnev, Gregory A. Fett, Arthur Griebel</i>		Crankshafts	173
and <i>John Tartaglia</i>	58	Induction Hardening of Camshafts	182
Introduction	58	Induction Hardening of Gears and Gear-Like Components	
Metallurgical Overview	58	<i>Valery Rudnev and John Storm</i>	187
Electromagnetic and Thermal Aspects	59	Introduction	187
Induction-Hardening Techniques	66	Gear Technology Overview	187
Inductors and Heat Pattern Control	70	Materials Selection	190
Quenching Techniques and Spray Quench		Gear-Hardening Patterns and Their Applicability	191
Subtleties	74	Tooth-by-Tooth Hardening versus Spin Hardening	192
Selection of Frequency, Power, and Heat Time	75	Through Heating for Surface Hardening	199
Case Depth Evaluation	78	Computer Modeling	200
Surface Hardness Evaluation	83	Inspection and Testing	202
Nondestructive Testing of Induction-Hardened		Typical Failures and Prevention	209
Parts	84	Induction Hardening Off-Road Machinery Components	
Quenching of Induction Heated Steel	87	<i>Marv McKimpson</i>	211
Quenching Process	87	Typical Applications	211
Hardening and Residual Stresses from		Materials for Induction Hardening	213
Quenching	88	Process Considerations	215
Quenching Methods	91	Process Validation	217
Quenchants	94	Equipment Considerations	219
Quenchant Maintenance	99	Future Prospects	220
Quench System Design	100	Induction Hardening for the Aeronautic and Aerospace Industry	
Troubleshooting Quenches	101	<i>Christian Krause and Fabio Biasutti</i>	222
		Requirements and Characteristics	222

Parts Applications and Materials	224	Superalloys	299
Process Monitoring	226	Copper Alloys	300
Economic Aspects	226	Carbon Steels and Alloy Steels Used in Warm and Hot Working	
Defects and Abnormal Characteristics of Induction Hardened Components		<i>Chester J. Van Tyne and Kester D. Clarke</i>	302
<i>Gregory A. Fett, Arthur Griebel, and John Tartaglia</i>	228	Microstructural Effects on Induction Heating of Steels	302
Prior Microstructure and Grain Size	228	Considerations for Induction Heating Various Steel Alloys	304
Decarburization	229	Forging Temperatures	305
Residual Stress	229	Composition Ranges for Steel Alloys	305
Carbon and Residual Alloy Content	229	Temperature Requirements for Heating Super Alloys and Stainless Steels	
Inclusions	229	<i>David U. Furrer, Pratt & Whitney</i>	306
Overheated or Burned Steel	230	Stainless Steel Alloys	306
Quench Cracks	230	Nickel-Base Superalloys	306
Barber Pole Effect	231	Induction Thermal Processing of Stainless Steels and Superalloys	307
Internal Cracks and Abnormal Grain Growth	232	Computational Modeling of Induction Heating Processes	309
Seams, Laps, and Other Magnetic Particle Indications	233	Temperature Requirements for Heating Titanium, Aluminum, Magnesium, and Copper Alloys	
Improper Hardness and Microstructure	234	<i>Alexey Sverdlin</i>	313
Mechanical Straightening Cracks	238	Aluminum and Its Alloys	313
Improper Case Depth	238	Copper Alloys	315
Iron Castings	239	Magnesium Alloys	315
		Titanium Alloys	317
		Resistivity and Conductivity of Aluminum, Copper, Titanium, and Magnesium Alloys	319
Modeling & Simulation Of Induction Heat Treating.	241	Induction Heating of Billets, Rods, and Bars	
Methods, Tools, and Software for Physical Process Analysis and Design		<i>Doug Brown, Valery Rudnev, and Peter Dickson</i>	330
<i>Michele Forzan</i>	243	Introduction	330
Static, Time-Dependent, Frequency Domain Coupled Problems, Multiphysics	243	Estimation of the Basic Process Parameters	331
Analytical Methods—Separation of Variables	245	Billet Heating Design Concepts	337
Finite-Difference Method	246	Induction Heating of Selective Regions	
Finite-Element Method with Energy Variational Method	249	<i>Valery Rudnev</i>	346
Volume Integral Mutually Coupled Circuits Method	251	End Heating of Bars, Rods, and Billets	347
Typical Structure of Numerical Simulation Codes	252	End Heaters Using Solenoid Coils	348
Electromagnetic Problem Solutions		Oval Coils	351
<i>Jerzy Barglik and Dagmara Dołęga</i>	261	Channel Inductors (Slot, Skid, or Tunnel Inductors)	352
Maxwell's Equations	261	Specifics of Computer Modeling of Bar and Billet End Heating	353
Mathematical Modeling of Electromagnetic Fields	262	Stress Relieving Selective Areas	354
Thermal Problem Solutions		Stress Relieving Pipe Ends	354
<i>Jerzy Barglik and Dagmara Dołęga</i>	266	Stress Relieving Welded Areas	356
Introduction	266	Selective Heating for Tube Bending	357
Mathematical Modeling	266	Other Applications and Inductor Designs	358
Coupled Problem Solution		Basic Principles of Optimal Design of Electromagnetic Devices and Multi-objective Optimization	
<i>Jerzy Barglik and Dagmara Dołęga</i>	269	<i>Paolo Di Barba</i>	359
Introduction	269	Design, Optimization, and Computational Electromagnetics	359
Weak Coupled Formulation	269	Multiobjective Formulation of a Design Problem	359
Quasi-Coupled Formulation	270	A Review of Pareto Optimality	360
Hard Coupled Formulation	270	Evolutionary Computing	362
Modeling and Simulation of Stresses and Distortion in Induction Hardened Steels		Field-Based Optimization Problems	362
<i>B. Lynn Ferguson and Zhichao Li</i>	272	Induction Heating of a Graphite Disk—Pancake Inductor	
Steel Chemistry and Microstructure	272	Optimal Design	363
Modeling of Austenite Formation and Decomposition	273	Results	364
Numerical Modeling of Stresses and Distortion	277	Conclusion	365
Cracking Issues	281	Optimal Control of Induction Heating of Metals Prior to Warm and Hot Forming	
Stresses Due to Induction Case Hardening	283	<i>Edgar Rapoport and Yulia Pleshivtseva</i>	366
Stress States Due to Induction Through Hardening	284	Optimization Problems for Induction Mass Heating Processes	366
		Method for Computation of Optimal Processes for Induction Heating of Metals	371
Induction Heating	291	Optimal Control of Static Induction Heating Processes	373
Warm and Hot Working Applications		Optimal Control of Progressive and Continuous Induction Heating Processes	390
<i>Chester J. Van Tyne and John Walters</i>	293	Combined Optimization of Technological Processes in a Complex Hot Metal Forming Operation	396
Plain Carbon and Low-Alloy Steels	293		
Microalloyed Forging Steels	295		
Stainless Steels	296		
Aluminum Alloys	297		
Titanium Alloys	298		

Induction Melting	403	Energy and Environmental Aspects of Induction Melting Processes <i>Egbert Baake and Bernard Nacke</i>	548
Introduction and Fundamental Principles of Induction Melting <i>Egbert Baake and Bernard Nacke</i>	405	Energy Demand of Various Melting Processes	548
Physical Principles of Induction Melting Processes	406	Improvement of the Efficiency of Melting Processes in Induction Crucible Furnaces	549
Fundamental Principles of Induction Crucible Furnaces	406	Energetic and Ecological Comparison of Different Melting Furnaces	550
Fundamental Principles of Channel Induction Furnaces	410	Energy and Power Management of Induction Melting Processes	552
Fundamental Principles of Induction Furnaces with Cold Crucible	413	Operating Safety of Induction Melting Furnaces <i>Manfred Hopf</i>	555
Fundamental Principles of Induction Skull Melting	414	General Monitoring and Supervision	555
Computational Modeling of Induction Melting and Experimental Verification <i>Andris Jakovics and Sergejs Pavlous</i>	416	Monitoring of Refractory Lining	555
Basic Thermal Phenomena	416	Methods of Wear Detection/Wear Monitoring	555
Basic Fluid Dynamics Phenomena	421	Equipment	563
Mass Transfer Phenomena	426	Fundamentals and General Aspects of Power Supply Design for Induction Heating, Heat Treating, Welding, and Melting <i>Michael Rugg and Gary Gariglio</i>	565
Turbulent Flow and Heat and Mass Exchange	428	Brief History of the Evolution of Induction Heating Systems	566
Numerical Computation of Fluid Flow	434	Power Electronics Components	567
Numerical Modeling of Turbulent Flow in an Induction Crucible Furnace	440	Power Supplies	568
Components and Design of Induction Crucible Furnaces <i>Erwin Dötsch and Bernard Nacke</i>	447	Electrical Circuits	569
Furnace Body	447	Induction Heating Power Supplies	570
Power Supply	452	Parallel versus Series Topology	572
Peripherals	456	Low-Frequency Power Supplies	572
Overall Layout	460	Power Supplies with Multiple Heat Stations	572
Components, Design, and Operation of Vacuum Induction Crucible Furnaces <i>Egbert Baake</i>	462	Power Supply Control	572
Vacuum Induction Furnaces	462	Special Considerations for Power Supplies	573
Components and Design of Channel Inductor Furnaces Furnace Vessel <i>Erwin Dötsch and Bernard Nacke</i>	467	System Design—Power Supply Selection	575
Channel Inductors	470	Heat Station Configurations	576
Power Supply	472	Power Supply Maintenance	576
Cooling Devices	473	Power Supplies for Induction Heat Treating, Brazing, and Soldering <i>Justin Mortimer, Andrew Bernhard, Carlos Rodriguez,</i> <i>Gregg Warner, and Tim Williams</i>	578
Metallurgy of Induction Melting Processes for Iron and Non-Iron Materials <i>Erwin Dötsch</i>	474	Example of Load Conditions for Single-Shot Heat Treating	578
Cast Iron	474	Load Conditions for Vertical Scanning	578
Cast Steel	483	Load Conditions for Brazing and Soldering	579
Aluminum	484	Typical Power Components Used in Induction Heat Treating, Brazing, and Soldering Power Supplies	579
Operation of Induction Furnaces in Iron Foundries <i>Erwin Dötsch</i>	491	Power Supply Types	580
Melting in Induction Crucible Furnaces	491	Inverters	581
Duplicating, Holding, and Combined Holding/Melting in the Crucible Furnace	503	Switching Devices	581
Holding in the Channel Furnace	505	Frequency-Multiplication Harmonic-Induction Power Supplies	581
Pouring with Pressure-Actuated Pouring Furnaces	511	Output Networks	583
Continuous Supply of Molten Iron	516	Simultaneous Dual-Frequency Induction Heating Power Supply	584
Operation of Induction Furnaces for Steel and Non-iron Materials <i>Erwin Dötsch</i>	521	Independently Controlled Frequency and Power (IFP) Induction Heating Power Supply	585
Induction Crucible Furnaces in Small Steel Works	522	Developments in Control Systems for Modern Induction Power Supplies	587
Induction Systems in the Aluminum Industry	525	The Future of Induction Heating Power Supplies	588
Induction Plants in Copper Foundries	529	Design and Fabrication of Inductors for Induction Heat Treating <i>Rob Goldstein, William Stuehr and Micah Black</i>	589
Induction Plant for Melting Zinc	531	Methods of Induction Heat Treating	589
Melting of Glasses and Oxides <i>Andris Jakovics and Sergejs Pavlous</i>	535	Considerations for Inductor Design	590
Physical Model of Inductor-Crucible Furnace (ICF)	535	Current Flow in the Part	590
Physical Model of Inductor Furnace with Cold Crucible (IFCC)	536	The Influence of Frequency	592
Dependence of Melt Properties on Temperature	537	Control of Heating in Different Areas of the Part	593
Correlation of Physical Fields and Melt Properties in ICF and IFCC	538	Presentation of the Part to the Inductor	594
Governing Equations and Boundary Conditions for ICF and IFCC Modeling	538	Inductor Structure	596
Peculiarities of EMF Modeling in IFCC	540	Coil Leads/Buswork and Contacts	597
Simulation of Skull Formation in IFCC	541	Quenching Considerations in Induction Coil Design	597
Results for Glasses and Skull Modeling in ICF	542	Induction Coil Cooling	598
		Case Study: Single-Shot Coil Copper Temperature Prediction	599
		Styles of Heat Treating Inductors	600

Skills for Heat Treating Inductor Construction	600	Horizontal Scanners	686
Attachment of Magnetic Flux Controllers	603	Tooth-by-Tooth Gear Hardening	688
Integrity Procedures prior to Production	604	Controlled Atmosphere Chambers	
Design and Fabrication of Induction Coils for Heating		<i>Scott Larrabee</i>	691
Bars, Billets, and Slabs		Types of Controlled Atmospheres	691
<i>Joe Stambaugh</i>	607	Controlled Atmosphere Chamber Selection Factors	695
Design Philosophies	607	Types of Controlled Atmosphere Chambers	697
Specific Designs	607	Material Handling Equipment for Induction Heating Systems	
Copper Coil Design and Construction for Forging Coils	608	<i>Sean Buechner and Brian P. Lockitski</i>	701
Induction Coil Electrical Insulation	611	Infeed Bar and Billet Handling Systems	701
Refractory Lining and Installation Practices for Induction		Induction Heating Feeding Systems	704
Heating Applications	613	Hot Billet Handling Systems	705
Wear Rails for Induction Coils	615	Maintenance of Induction Heat Treating Equipment	
Applying Power for the First Time	617	<i>Fred R. Specht</i>	709
Preventive Maintenance for Induction Forging Coils	617	Hardness Test Equipment	709
Conclusion	618	Power Supplies and Heat Stations	709
Design and Fabrication of Inductors for Heat Treating,		Controls, Programmable Logic Controllers, and	
Brazing, and Soldering		Computer Systems	710
<i>Scott Larrabee and Andrew Bernhard</i>	619	Water Cooling Systems	710
Materials Used for Inductor (Coil) Construction	619	Fixtures and Machines	711
General Inductor Construction, Fabrication, and Power Supply		Air Operated or Pneumatic Devices	711
Mounting Techniques	623	Coils and Bus Work	711
Inductor Designs	624	Quench Systems	712
Key Inductor Design Variables	626	Moving and Storage of Induction Equipment	713
Designing for Dissimilar Materials	629	Conclusion	713
Magnetic Flux Controllers in Induction Heating and Melting		Water Cooling for Induction Systems	
<i>Robert Goldstein</i>	633	<i>Fred R. Specht</i>	714
Magnetic Circuits in Induction Applications	633	Recirculating Water Systems for Power Supplies	714
Role of Magnetic Flux Controllers in Induction Systems	633	Cooling Towers	716
Materials for Magnetic Flux Control	634	Air-Cooled Heat Exchangers	716
Design Guidelines for Using Magnetic Flux Controllers on		Air-Cooled Heat Exchangers with Trim Cooler	716
Induction Coils	635	Closed-Circuit Evaporative Cooling Towers	717
Effects of Magnetic Flux Controllers on Common Coil Styles	635	Open Evaporative Cooling Towers	717
Cooling of Magnetic Flux Controllers	637	Placement of Cooling Towers	717
Determining the Thickness of Soft Magnetic Material	639	Refrigerant Chillers	720
Channel Type Furnaces	639	Summary	720
Crucible Type Furnaces	639		
Cold-Crucible Melting Furnaces	640	Process Control, Monitoring, Design and Quality Assurance	721
Magnetic Flux Control in Mass-Heating Applications	641	Process Control, Monitoring and Quality Insurance	
Magnetic Flux Control in Induction Tube-Welding		Specifics for Induction Heating	
Applications	642	<i>Timothy Kennamer</i>	723
Magnetic Flux Control in Local Heat Treating		Process Control Modes	724
Applications	643	Process Monitoring Requirements	724
Systematic Analysis of Induction Coil Failures and Prevention		Metallurgical Destructive Testing versus Monitoring	727
<i>Valery Rudnev</i>	646	Programmable Logic Controllers	727
Basics of the Induction Coil	646	System Design Concerns	728
Effect of Current Flow on Crack Propagation	647	Using Infrared Thermometers to Control Temperature	
Coil Copper Selection	650	During Induction Heating	
Electromagnetic Edge Effect of Coil Copper Turn	651	<i>Vern Lappe</i>	730
Effect of Magnetic Flux Concentrators on Coil Life	653	Infrared Theory	730
Coil End Effect	656	How an Infrared Thermometer Works	732
Fabrication of Hardening Inductors	657	How to Choose the Correct Instrument	733
Tooth-by-Tooth Gear-Hardening Inductors	659	Installation and Maintenance	735
Clamshell Inductors	660	Applications	737
Contactless Inductors	661	Thermal Imagers	739
Inductors for Heating Internal Surfaces	662	Induction Heating Control System	
Split-Return Inductors and Butterfly Inductors	665	<i>Michael Rugg</i>	742
Electromagnetic Proximity Effect	667	Machine Controller/Interface Wiring	742
Proper Electrical Contacts	668	Operator Interface	742
Conclusion	670	Safety Control	743
Transformer Design and Load Matching		Power Supply, Operator Interface, and Machine Programming	743
<i>Ray Cook and Bill Terlop</i>	673	Temperature Control Descriptions and Programming	743
Transformers and Reactors for Induction Heating	673	Conclusion	745
Load Matching	678	Process Design for Induction Brazing and Soldering	
Vertical Scanners, Horizontal Scanners, and Tooth by Tooth Scanners		<i>R. Gene Stout</i>	746
<i>Ronald R. Akers</i>	683	Soldering versus Brazing	746
Vertical Scanners	683		

Cleaning the Parts Before Soldering or Brazing	747	Normal Exposure Levels	770
Solder Filler Metals	748	Exposure Levels in Professional Environments.	772
Soldering Fluxes.	748	Government Oversight	773
Solderability of Copper-Base Metals.	748		
Common Soldered Joint Defects.	748	Special Applications Of Induction Heating.	781
Brazing Filler Metals	748	Historical Review of Induction Glass Melting	
Types of Base Metals that Can Be Joined by Soldering or Brazing	749	<i>David J. McEnroe</i>	783
Joint Strength and Types of Joint Designs.	749	Induction Heating History	784
Selecting the Right Induction Heating Equipment.	750	Induction Glass Melting and Forming	
Determining Joint Quality	750	<i>David J. McEnroe</i>	787
Establishing a Reliable Process	751	Basics of Glass Fabrication	787
Using Automation to Join Parts	751	Melting	787
Documenting the Process.	752	Forming.	791
Conclusion.	753	Induction versus Refractory	793
Inspection and NDT Methods		Induction Heating in Optical Fiber Draw Processing	
<i>Vladimir Frankfurt and Philip Nash</i>	754	<i>Daniel W. Hawtof</i>	795
In-Process Inspection	754	Fiber Draw Tension	795
Destructive Methods	755	Temperature Requirements	795
Nondestructive Evaluation	756	Ambient Heating Environment.	797
Control of Professional Magnetic Field Exposure—International Standards and Regulations		Heated Part Size.	797
<i>Loris Koenig</i>	767	Susceptor Materials Selection.	797
Electromagnetic Field	767	Nanoparticle Heating Using Induction in Hyperthermia	
Concerns about Effects on Health.	768	<i>Girish Dahake</i>	799
Direct Effects on Health	768	Nanoparticles	799
Possible Indirect Effects on Health	769	Induction Heating	799
		Index	801

