

TENTH EDITION

WELDING HANDBOOK

VOLUME 1

Welding and Cutting Science and Technology



Welding Handbook

Tenth Edition

Volume 1

WELDING AND CUTTING SCIENCE AND TECHNOLOGY

Prepared under the direction of the
Welding Handbook Committee

Kathy Sinnes
Editor



American Welding Society

8669 NW 36 St, # 130

Miami, FL 33166

Welding Handbook, Tenth Edition

Volume 1 *Welding and Cutting Science and Technology*

Projected:

Volume 2 *Welding Processes—Arc Welding and Cutting*

Volume 3 *Welding Processes—Resistance, Solid-State, Oxyfuel, Brazing, and Soldering*

Volume 4 *Materials and Applications—Ferrous and Surfacing Metals, and Maintenance and Underwater Applications*

Volume 5 *Materials and Applications—Nonferrous and High-Temperature Metals, and Nonmetallic Materials*

© 2018 by American Welding Society
All rights reserved
First Printing: November, 2018

No portion of this book may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, including mechanical, photocopying, recording, or otherwise, without the prior written permission of the copyright owner.

Authorization to photocopy items for internal, personal, or educational classroom use only, or the internal, personal, or educational classroom use only of specific clients, is granted by the American Welding Society (AWS) provided the appropriate fee is paid to the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923; telephone: (978) 750-8400; Internet: www.copyright.com.

Library of Congress Control Number: 2018953522
Print—ISBN: 978-1-64322-014-7
PDF—ISBN: 978-1-64322-015-4

The *Welding Handbook* is the result of the collective effort of many volunteer technical specialists who provide information to assist with the design and application of welding and allied processes.

The information and data presented in the *Welding Handbook* are intended for informational purposes only. Reasonable care is exercised in the compilation and publication of the *Welding Handbook* to ensure the authenticity of the contents. However, no representation is made as to the accuracy, reliability, or completeness of this information, and an independent, substantiating investigation of the information should be undertaken by the user.

The information contained in the *Welding Handbook* shall not be construed as a grant of any right of manufacture, sale, use, or reproduction in connection with any method, process, apparatus, product, composition, or system, which is covered by patent, copyright, or trademark. Also, it shall not be construed as a defense against any liability for such infringement. Whether the use of any information in the *Welding Handbook* would result in an infringement of any patent, copyright, or trademark is a determination to be made by the user.

Printed in the United States of America

DEDICATION

Harvey R. Castner

*In recognition of his distinguished service
to the welding industry and his
enduring contributions to the Welding Handbook*

Harvey R. Castner—welding engineer, manager, researcher, mentor, and welding industry expert—used his extensive technical expertise to expand the technology of welding for today and future generations. He generously shared the knowledge acquired during his career in the welding industry by serving on various industry committees, including the *Welding Handbook* Committee. He joined AWS in 1962 and has been active throughout his working career.

Harvey served as a *Welding Handbook* chapter volunteer beginning in the early 1990s and became a Committee member in 1993. He has provided valuable guidance to the Committee on the organization and technical content, serving as the *Welding Handbook* Committee Chair from 1999 to 2004. He continued providing support after his term as Chair through oversight and final reviews of various chapters in subsequent volumes of the 9th edition.

He holds a B.S. degree in Welding Engineering from The Ohio State University and an M.B.A. from Kent State University. He began his career at Allis Chalmers Corporation in Milwaukee Wisconsin and moved on to the Edison Welding Institute in Columbus, Ohio. He served not only as a welding engineer, but also as a project manager and senior technical manager, leading various research projects. He is a Fellow of the American Welding Society, an AWS Life Member, and recipient of the James F. Lincoln Gold Medal Award. He is also a past member of the AWS Board of Directors. Harvey has tirelessly worked for the improvement of the greater welding community through his technical research, and development of the next generation of welding personnel.

The *Welding Handbook* Committee is honored to dedicate this Volume to Harvey R. Castner for his loyal devotion and service to AWS and the *Welding Handbook*.

CONTENTS

DEDICATION	v
ACKNOWLEDGMENTS	xi
PREFACE	xii
REVIEWERS	xiii
CONTRIBUTORS	xiv

PART I—THE SCIENCE OF WELDING, CUTTING, AND ALLIED PROCESSES

CHAPTER 1—SURVEY OF JOINING, CUTTING, AND ALLIED PROCESSES	1
Introduction	2
Joining Processes	3
Resistance Welding	19
Cutting Processes	48
Thermal Spraying	53
Conclusion	55
Bibliography	55
Supplementary Reading List	56
CHAPTER 2—PHYSICS OF WELDING AND CUTTING	58
Introduction	58
Fusion and Solid-State Welding	58
Energy Sources for Welding	64
Arc Characteristics	74
Metal Transfer	80
Melting Rates	87
Physical Properties of Metals and Shielding Gases	93
Conclusion	96
Bibliography	96
Supplementary Reading List	96
CHAPTER 3—HEAT FLOW IN WELDING	87
Introduction	100
Fundamentals of Heat Flow	101
Quantitative Calculation of Heat Transfer in Fusion Welding	107
Conduction of Heat during Fusion Welding	110
Convective Heat Transfer in the Weld Pool	117
Relative Importance of Conduction and Convection	119
Heat Flow in Dissimilar Welding	123
Heat Flow in Solid-State Welding	125
Conclusion	128
Bibliography	129
Supplementary Reading List	130
CHAPTER 4—WELDING METALLURGY	115
Introduction	132
Physical Metallurgy	132
Metallurgy of Welding	147
Weldability of Some Commercial Alloys	158
The Brazed or Soldered Joint	168
Corrosion in Weldments	171
Conclusion	175
Bibliography	175
Supplementary Reading List	176
CHAPTER 5—DESIGN FOR WELDING	157
Introduction	180

Connection Design	180
Basics of Welded Connections	183
Principles of Connection Design	191
Economics of Welding	201
Quality and Connection Design Detailing	203
Detailing of Welds	215
Sizing of Steel Welds	229
Special Conditions	249
Other Alloys	270
Examples	281
Conclusion	289
Bibliography	289

PART II—DESIGN CONSIDERATIONS

CHAPTER 6—SYMBOLS FOR JOINING AND INSPECTION	291
Introduction	292
Fundamentals	292
Weld Symbols	293
Welding Symbols	293
Welding Symbols for Specific Weld Types	307
Brazing Symbols	313
Soldering Symbols	314
Nondestructive Examination Symbols	317
Conclusion	324
Bibliography	325
Supplementary Reading List	325

CHAPTER 7—RESIDUAL STRESS AND DISTORTION	327
Introduction	328
Fundamentals	328
Nature and Causes of Residual Stress	332
Effects of Residual Stress	337
Measurement of Residual Stress in Weldments	344
Residual Stress Distribution Patterns in Typical Welds	353
Effects of Welding Sequence on Residual Stress	358
Residual Stress and Distortion in Welds Made with Different Welding Processes	361
Computational Weld Modeling	361
Weld Distortion	369
Reducing or Controlling Residual Stress and Distortion	396
Conclusion	411
Bibliography	411
Supplementary Reading List	415

CHAPTER 8—ECONOMICS OF WELDING AND CUTTING	417
Introduction	418
The Cost Estimate	418
Economics of Welding	419
Automated and Robotic Systems	433
Economics of Resistance Spot Welding	444
Capital Investment in Welding Automation and Robotics	447
Control of Welding Costs	451
Economics of Brazing and Soldering	456
Economics of Thermal Cutting	462
Conclusion	464
Bibliography	465
Supplementary Reading List	465

PART III—AUTOMATION OF JOINING PROCESSES

CHAPTER 9—MECHANIZED, AUTOMATED, AND ROBOTIC WELDING	467
Introduction	468
Mechanized Welding and Cutting.....	468
Automated Welding.....	474
Robotic Welding.....	482
Planning for Automated and Robotic Welding	491
Conclusion	499
Bibliography	499
Supplementary Reading List	499
CHAPTER 10—WELDMENT TOOLING AND POSITIONING.....	501
Introduction	502
Fixtures	502
Positioners.....	509
Conclusion	528
Bibliography	528
Supplementary Reading List	528
CHAPTER 11—MONITORING AND CONTROL OF WELDING AND JOINING PROCESSES	529
Introduction	530
Principles of Monitoring and Control.....	531
Sensing Devices	532
Process Instrumentation	542
Process Monitoring Systems	542
Process Control Systems	543
Monitoring and Control Systems.....	545
Conclusion	566
Bibliography	566
Supplementary Reading List	566

PART IV—QUALITY, TESTING STANDARDS, AND METHODS

CHAPTER 12—WELD QUALITY	571
Introduction	572
Defining Weld Quality.....	572
Overview of Weld Discontinuities.....	574
Discontinuities Associated with Fusion Welding.....	575
Discontinuities Associated with Resistance Welding	600
Discontinuities Associated with the Solid-State Welding Processes.....	605
Discontinuities in Brazed and Soldered Joints.....	607
Significance of Weld Discontinuities	610
Conclusion	613
Bibliography	614
Supplementary Reading List	614
CHAPTER 13—TEST METHODS FOR EVALUATING WELDED JOINTS	617
Introduction	618
Testing for Strength	619
Hardness Testing	633
Bend Testing	640
Fracture Toughness Testing.....	642
Fatigue Testing	653
Corrosion Testing.....	658
Creep and Rupture Testing	662
Testing of Thermal Spray Applications	664

Weldability Testing.....	667
Conclusion.....	676
Bibliography.....	676
Supplementary Reading List.....	680

CHAPTER 14—WELDING INSPECTION AND NONDESTRUCTIVE EXAMINATION.....681

Introduction.....	682
Personnel Qualifications.....	683
The Inspection Plan.....	685
Nondestructive Examination.....	686
Metallographic Examination Methods.....	739
Inspection of Brazed and Soldered Joints.....	740
Conclusion.....	740
Bibliography.....	740
Supplementary Reading List.....	742

CHAPTER 15—PERSONNEL QUALIFICATION AND CERTIFICATION 743

Introduction.....	744
Welding and Brazing Procedure Specifications.....	747
Qualification of Welding and Brazing Procedures.....	761
Performance Qualification.....	769
Standardization of Qualification Requirements.....	789
Conclusion.....	789
Bibliography.....	789
Supplementary Reading List.....	791

CHAPTER 16—CODES AND OTHER STANDARDS 793

Introduction.....	794
Types of Regulatory Documents.....	794
Standards-Developing Organizations and Welding-Related Publications.....	795
Guidelines for Participating in International Standards Activities.....	818
Conclusion.....	819
Supplementary Reading List.....	819

PART V—SAFETY AND HEALTH

CHAPTER 17—SAFE PRACTICES.....822

Introduction.....	822
Safety Management.....	822
Protection of the Work Area.....	826
Personal Protective Equipment.....	829
Protection against Fumes and Gases.....	834
Safe Handling of Compressed Gases.....	843
Protection against Electromagnetic Radiation.....	848
Electrical Safety.....	849
Fire Prevention and Protection.....	852
Explosion Prevention.....	854
Process-Specific Safety Considerations.....	854
Safety in Robotic Operations.....	866
Conclusion.....	871
Bibliography.....	871
Supplementary Reading List.....	873

INDEX OF TENTH EDITION, Volume 1 875

ACKNOWLEDGMENTS

The Welding Handbook Committee of the American Welding Society and the editor gratefully recognize the contributions of the volunteers who have created, developed, and documented the technology of welding and shared it in past editions of the *Welding Handbook*, beginning with the first edition published in 1938. The enthusiasm and meticulous dedication of the authors and technologists reflected in the previous nine editions of the *Welding Handbook* are continued in this volume of the tenth edition.

This volume was compiled by the members the Welding Handbook Volume 1 Committee and the WH1 Chapter Committees, with oversight by the Welding Handbook Committee. Chapter committee chairs, chapter committee members, and oversight persons are recognized on the title pages of the chapters.

The Welding Handbook Committee and the editor recognize and appreciate the AWS technical committees who developed the consensus standards that pertain to this volume, and acknowledge the work of the editors of all previous editions. The Welding Handbook Committee is grateful to members of the AWS Technical Activities Committee and the AWS Safety and Health Committee for their reviews of the chapters. The editor appreciates the AWS Publications staff and Standards Development staff for their assistance during the preparation of this volume.

Welding Handbook Committee Chairs, 1938–2015

1938–1942	<i>D. S. Jacobus</i>
Circa 1950	<i>H. L. Boardman</i>
1956–1958	<i>F. L. Plummer</i>
1958–1960	<i>R. D. Stout</i>
1960–1962	<i>J. F. Randall</i>
1962–1965	<i>G. E. Claussen</i>
1965–1966	<i>H. Schwartzbart</i>
1966–1967	<i>A. Lesnewich</i>
1967–1968	<i>W. L. Burch</i>
1968–1969	<i>L. F. Lockwood</i>
1969–1970	<i>P. W. Ramsey</i>
1970–1971	<i>D. V. Wilcox</i>
1971–1972	<i>C. E. Jackson</i>
1972–1975	<i>S. Weiss</i>
1975–1978	<i>A. W. Pense</i>
1978–1981	<i>W. L. Wilcox</i>
1981–1984	<i>J. R. Condra</i>
1984–1987	<i>J. R. Hannahs</i>
1987–1990	<i>M. J. Tomsic</i>
1990–1992	<i>C. W. Case</i>
1992–1996	<i>B. R. Somers</i>
1996–1999	<i>P. I. Temple</i>
1999–2004	<i>H. R. Castner</i>
2004–2007	<i>P. I. Temple</i>
2007–2009	<i>C. E. Pepper</i>
2009–2014	<i>Wangen Lin</i>
2015–	<i>D. D. Kautz</i>