

TENTH EDITION

WELDING HANDBOOK

VOLUME 1

Welding and Cutting Science and Technology



Documents
Document Sharing Hub

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*



Welding Handbook

Tenth Edition

Volume 1

**WELDING AND CUTTING
SCIENCE AND TECHNOLOGY**



American Welding Society

© 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>

PREFACE

This volume of the *Welding Handbook* presents an overview of the most recent research and engineering developments in the field of welding and cutting science and technology. Upcoming volumes will address welding processes, materials, and applications. Together, the five volumes of the tenth edition substantially expand upon and update the information presented in the ninth edition.

The seventeen chapters in this volume cover the fundamentals of welding, cutting, joining, and allied processes. The chapters discuss metallurgy, the physics of welding and cutting, heat flow in welding, and residual stress and distortion. Other important topics include engineering considerations of weld design, weldment tooling and positioning, automation, process monitoring and control, methods for the evaluation and testing of welds, weld quality, weld inspection and nondestructive examination, and the economics of welding.

Well-researched chapters on codes and other standards, the qualification and certification of welding techniques and personnel, the accurate communication of welding information, and safe practices are also included. The information in this volume is applicable to all categories of welding, from manual welding to the most sophisticated automated and robotic systems.

The peer-reviewed chapters in this volume are enhanced by the pertinent consensus standards that are referenced throughout. More than 700 drawings, schematics, and photographs illustrate the text. Approximately 170 tables provide categorized or comparative information. Explanatory information and sources are identified and referenced in footnotes.

This volume, like the others preceding it, is a voluntary effort by the members of the Welding Handbook Committee, the Welding Handbook Volume 1 Committee, and the Chapter Committees. Each chapter is reviewed by members of the American Welding Society's Technical Activities Committee (TAC), Safety and Health Committee (SHC), and other specialists.

D. D. Kautz, Chair
Welding Handbook Committee
2015–Present

Kathy Sinnes, Editor
Secretary
Welding Handbook Committee

REVIEWERS

AMERICAN WELDING SOCIETY SAFETY AND HEALTH COMMITTEE TECHNICAL ACTIVITIES COMMITTEE

G. L. Alexy	<i>Alexy Metals</i>
D. R. Atkins	<i>Unified Engineering, Inc.</i>
D. M. Beneteau	<i>CenterLine (Windsor) LTD</i>
J. E. Campbell	<i>Machinery & Welder Corporation</i>
D. E. Clark	<i>DEClark Welding Engineering, PLLC</i>
T. M. Donovan	<i>Los Alamos National Security, LLC</i>
D. A. Fink	<i>The Lincoln Electric Company</i>
S. R. Fiore	<i>Hobart Brothers Company</i>
M. Haaksma	<i>Orange County Ironworks, LLC</i>
W. A. Komlos	<i>Arc Tech, LLC</i>
W. E. Layo	<i>Midalloy</i>
P. S. Lester	<i>Novelis</i>
S. O. Luke	<i>Black & Veatch</i>
W. F. Newell	<i>W F Newell & Associates</i>
R. M. Santasiero	<i>Central Arizona College</i>
J. J. Sekely	<i>Welding Services, Inc.</i>
A. W. Sindel	<i>Alstom Power, Incorporated</i>
W. J. Sperko	<i>Sperko Engineering Services</i>

CONTRIBUTORS

WELDING HANDBOOK COMMITTEE

D. D. Kautz, Chair	<i>Los Alamos National Laboratory</i>
G. A. Young, 1st Vice Chair	<i>Lone Star Thermal Engineering</i>
M. D. Hayes, 2nd Vice Chair	<i>Acute Technological Services</i>
Wangen Lin, Past Chair	<i>Pratt & Whitney</i>
K. Sinnes, Secretary	<i>American Welding Society</i>
B. J. Bastian	<i>Benmar Associates</i>
J. E. Beckham	<i>Fiat Chrysler, Automobiles US, LLC</i>
S. K. Chimbli	<i>Stress Engineering Services</i>
M. E. Gase	<i>Midwest Steel, Inc.</i>
T. A. Palmer	<i>Pennsylvania State University</i>
C. E. Pepper	<i>Southeastern Louisiana University</i>
J. J. Perdomo	<i>ExxonMobile Research and Engineering Co.</i>
P. I. Temple	<i>eNergyWise Consulting, LLC</i>

WELDING HANDBOOK VOLUME 1 COMMITTEE

D. D. Kautz, Chair	<i>Los Alamos National Laboratory</i>
G. A. Young, 1st Vice Chair	<i>Lone Star Thermal Engineering</i>
M. D. Hayes, 2nd Vice Chair	<i>Acute Technological Services</i>
Wangen Lin, Past Chair	<i>Pratt & Whitney</i>
K. Sinnes, Secretary	<i>American Welding Society</i>
J. E. Beckham	<i>Fiat Chrysler, Automobiles US, LLC</i>
S. K. Chimbli	<i>Stress Engineering Services</i>
M. E. Gase	<i>Midwest Steel, Inc.</i>
T. A. Palmer	<i>Pennsylvania State University</i>
J. J. Perdomo	<i>ExxonMobile Research and Engineering Co.</i>
C. E. Pepper	<i>Southeastern Louisiana University</i>
R. W. Warke	<i>Wiss, Janney, Elstner Associates, Inc.</i>

CHAPTER CHAIRS

Chapter 1	J. E. Beckham	Fiat Chrysler, Automobiles US, LLC
Chapter 2	D. F. Farson	The Ohio State University
Chapter 3	D. K. Aidun	Clarkson University
Chapter 4	J. J. Perdomo	ExxonMobil Research and Engineering Company
Chapter 5	D. K. Miller	The Lincoln Electric Company
Chapter 6	J. J. Gullotti	Consultant
Chapter 7	F. W. Brust	Engineering Mechanics Corporation of Columbus (Emc ²)
Chapter 8	S. K. Chimbli	Stress Engineering Services
Chapter 9	L. K. Gross	Milwaukee Area Tech College
Chapter 10	C. W. White	Koike Aronson/Ransome
Chapter 11	D. D. Schwemmer, Jr.	AMET, Inc.
	M. D. Hayes	Acute Technological Services—Oil States Industries
Chapter 12	B. R. Krueger	Los Alamos National Laboratory
Chapter 13	C. E. Cross	Los Alamos National Laboratory
Chapter 14	M. E. Gase	Midwest Steel, Inc.
Chapter 15	S. P. Brannock	Hensel Phelps Construction Co.
Chapter 16	C. E. Pepper	Southeastern Louisiana University
Chapter 17	S. R. Fiore	Hobart Brothers Company

CHAPTER 1

SURVEY OF
JOINING, CUTTING,
AND ALLIED
PROCESSES

Prepared by the
Welding Handbook
Chapter Committee
on Joining and
Cutting Processes:

J. E. Beckham, Chair
*Fiat Chrysler Automobiles
US, LLC*

R. L. Mertz
Alta Vista Solutions

W. A. Komlos
Arc Tech, LLC

M. D. Wilson
HSB Global Standards

Dr. Y. Adonyi
LeTourneau University

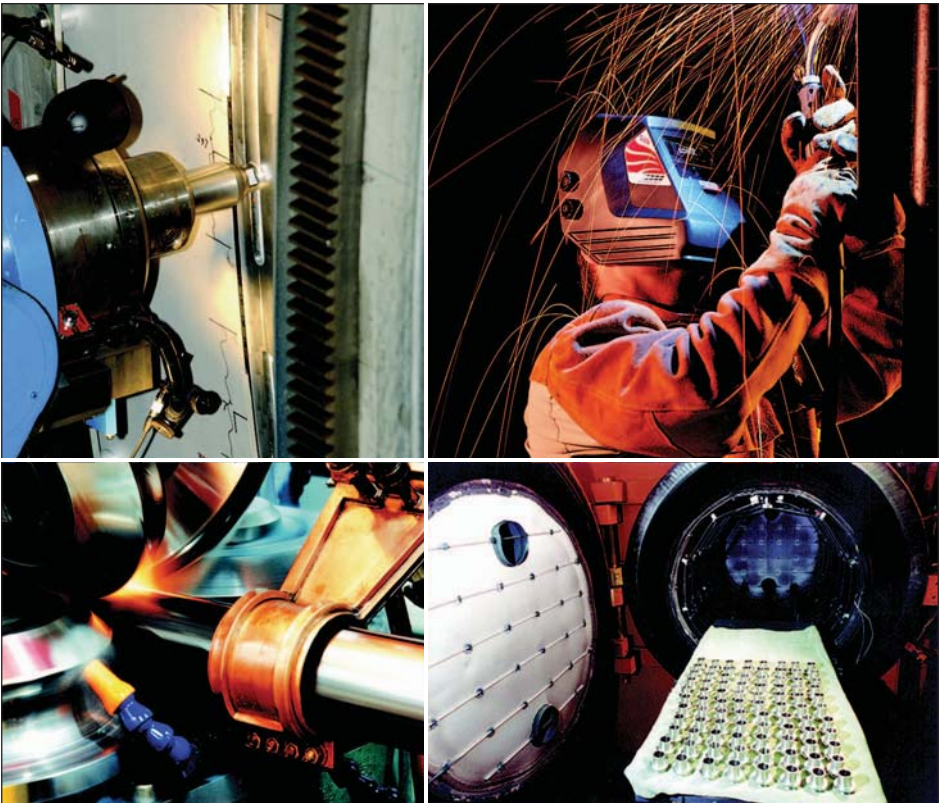
C. W. O'Brien
*Fiat Chrysler Automobiles
US, LLC*

Welding Handbook
Committee Member:

D. D. Kautz
*Los Alamos National
Laboratory*

Contents

Introduction	2
Joining Processes	3
Resistance Welding	19
Cutting Processes	48
Thermal Spraying	53
Conclusion	55
Bibliography	55
Supplementary Reading List	56



Top Left: Photograph courtesy of Gas Flux Company; Top Right: Photograph courtesy of The Lincoln Electric Company;
Bottom Left: Photograph courtesy of EFD Induction; Bottom Right: Photograph courtesy of HiTecMetal Group.

CHAPTER 1

SURVEY OF JOINING, CUTTING, AND ALLIED PROCESSES

INTRODUCTION

This chapter introduces the basic concepts of the conventional and more widely used joining, cutting, and thermal spraying processes. The distinguishing features of the various processes are summarized and compared to one another. Among the joining processes reviewed are the electric arc, resistance, and solid-state welding processes as well as brazing, soldering, and adhesive bonding. The cutting processes examined include thermal and nonthermal methods of material removal. Thermal spray processes, including flame spraying (FLSP), plasma arc spraying, arc spraying, and detonation flame spraying, will also be reviewed in this chapter.^{1, 2, 3}

Several processes may be applicable for a specific job; the challenges include selecting the process that is most suitable for the specific application, code requirements, schedule, and cost. However, these factors may not be compatible with each other and may require a

compromise. The selection of the optimum process ultimately depends on several criteria, including the number of components to be fabricated, capital equipment costs, joint location, structural mass, and the preferred performance of the product. The adaptability of the process to the location of the operation, the type of manufacturing environment, and the experience and skill levels of the employees may also have an impact on the final selection. In this chapter, these criteria are examined as they relate to the various joining, cutting, and thermal spraying processes.

This chapter is intended to serve as a survey of the most common joining, cutting, and thermal spraying processes; therefore the reader is encouraged to conduct a thorough investigation of the processes that appear to have the best potential for the intended applications. This investigation should consider safety and health recommendations such as those presented in the American National Standard *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1,⁴ and the information provided in the manufacturers' safety data sheet (SDS). Additional sources of information about the joining, cutting, and allied processes are listed in the Bibliography and Supplementary Reading List at the end of this chapter. In particular, *Welding Processes*,⁵ Volume 2 and Volume 3 of the American Welding Society's *Welding Handbook*, presents in-depth coverage of each of the processes.

1. Welding terms and definitions used throughout this chapter are from American Welding Society (AWS) Committee on Definitions and Symbols, *Standard Welding Terms and Definitions, Including Terms for Adhesive Bonding, Brazing, Soldering, Thermal Cutting, and Thermal Spraying*, AWS A3.0M/A3.0, Miami: American Welding Society.

2. At the time this chapter was prepared, the referenced codes and other standards were valid. If a code or other standard is cited without a date of publication, it is understood that the latest edition of the referenced document applies. If a code or other standard is cited with the date of publication, the citation refers to that edition only, and it is understood that any future revisions or amendments to the code are not included; however, as codes and standards undergo frequent revision, the reader should consult the most recent edition.

3. The AWS *Welding Handbook* makes use of both U.S. Customary Units and the International System of Units (SI). The latter are shown within parentheses () in the text and in appropriate columns in tables and figures. SI measurements may not be exact equivalents; therefore, each system must be used independently.

4. American National Standards Institute (ANSI), *Safety in Welding, Cutting, and Allied Processes*, ANSI Z49.1, Miami: American Welding Society.

5. American Welding Society (AWS) Welding Handbook Committee, 2004, *Welding Processes*, Part 1, Vol. 2 and 2007, *Welding Processes*, Part 2, Vol. 3 of *Welding Handbook*, 9th ed., Miami: American Welding Society.

JOINING PROCESSES

The goal of all joining processes is to combine individual pieces of material into a single component. In the case of two pieces of compatible metal, if the atoms at the contacting surface of one piece come close enough to the atoms at the contacting surface of the other piece, then interatomic pull will develop and the two pieces will become one. Although this concept is easy to describe, it does not usually happen under typical conditions.

Surface roughness, impurities, fitting imperfections, and the varied properties of the materials make it nearly impossible for this ideal scenario to occur so thermal (heat) and mechanical energy (pressure) is required to eliminate these barriers and thereby make joining possible. Welding processes and procedures have been developed to provide the thermal, mechanical or a combination of both energies required to overcome these difficulties and to activate the adjoining surfaces.

Most welding processes apply significant thermal energy to the base material which can reach temperatures that can be ten times the melting temperature of the base metal, causing melting and vaporization. The temperatures that are reached in many of the welding processes typically cause changes in the base metal microstructure and composition which can be detrimental to the properties of the materials being joined. Hot metals tend to oxidize rapidly at elevated temperatures so sufficient protection must be provided to prevent this detrimental reaction. Some metals are more sensitive than others, in which case protection from oxidation can become more demanding. The method by which sufficient protection against oxidation is provided by the process should then be identified. When determining which welding process to use, one must consider what effect the heat input from each of the welding processes being evaluated will have on the base metal, weld passes, as well as how any of the resulting microstructural changes will impact the function of the components being joined.

The selection of an appropriate joining and cutting process for a given task involves a number of considerations. These include the following:

1. Availability of the welding process;
2. Suitability of the welding process for the environment in which welding is to be done;
3. Skill requirements;
4. Weldability of the base metals with respect to type and thickness to be joined;
5. Availability of suitable welding consumables;
6. Weld joint design;
7. Heat input requirements;
8. Demands of the welding position;

9. Cost of the process, including capital expenditures, materials, and labor;
10. Number of components to be fabricated;
11. Delivery requirements;
12. Applicable code and/or standard requirements; and
13. Safety concerns.

The overview of the joining processes featured in Table 1.1 presents an initial reference guide to the capabilities of various joining processes with respect to a variety of ferrous and nonferrous metals. This table indicates the processes, materials, and material thickness combinations that are typically compatible. The columns on the left list various engineering materials and four arbitrary thickness ranges. The processes most commonly used in industry are listed across the top.

It should be noted that additional information, such as the considerations listed above, must be taken into account before process selections are finalized. Table 1.1 can be a useful tool in providing general guidelines for the screening and selection process. In addition, six-sigma methodologies, such as Failure Effect Mode Analysis, or FMEA, can also be useful to minimize the potential causes of failure during the evaluation process.

ARC WELDING

The term *arc welding* applies to a large, diversified group of welding processes that use an electric arc as the source of heat. The creation of a weld between metals using these processes does not usually involve pressure. The process may or may not utilize a filler metal. The arc is initiated between the workpiece and the tip of the electrode. The intense heat produced by the arc melts the base metal in the area of the arc which upon cooling results in the formation of a weld. The electric arc may be either moved along the joint to produce the weld or held stationary while the workpiece is moved under the process.

Arc welding can be performed by conducting the welding current through consumable electrodes such as a wire or rod, or it can be done using nonconsumable electrodes of carbon or tungsten rods. Metal arc processes utilize consumable electrodes that melt the electrode filler metal along with the base metal to create the weld. Some arc welding processes may also produce a slag covering to protect the molten metal from oxidation or support out-of-position welding.

The nonconsumable arc processes generate a weld by melting the base metal only, resulting in what is termed an *autogenous weld*. The nonconsumable electrode serves only to sustain the arc. If filler metal is required in a nonconsumable process, it may be fed either manually or mechanically into the molten weld pool.

Table 1.1
Capabilities of the Commonly Used Joining Processes

		Processes																							
		S M A W	S A W	G M A W	F C A W	G T A W	P A W	E S W	E G W	R W	F W	O F W	D F W	F R W	E B W	L B W	T B	F B	R B	I B	D B	I R B	D F B	S	
Carbon steel	S	x*	x	x		x				x	x	x			x	x	x	x	x	x	x	x	x	x	
	I	x	x	x	x	x				x	x	x		x	x	x	x	x	x	x	x	x	x	x	
	M	x	x	x	x					x	x	x		x	x	x	x	x	x				x	x	
	T	x	x	x	x			x	x		x	x		x	x	x		x	x				x	x	
Low-alloy steel	S	x	x	x		x				x	x	x	x		x	x	x	x	x	x	x	x	x	x	
	I	x	x	x	x	x				x	x		x	x	x	x	x	x	x				x	x	
	M	x	x	x	x					x	x		x	x	x	x	x	x	x				x	x	
	T	x	x	x	x			x			x		x	x	x		x					x		x	
Stainless steel	S	x	x	x		x	x			x	x	x	x		x	x	x	x	x	x	x	x	x	x	
	I	x	x	x	x	x	x			x	x		x	x	x	x	x	x	x				x	x	
	M	x	x	x	x		x				x		x	x	x	x	x	x	x				x	x	
	T	x	x	x	x			x			x		x	x	x			x					x	x	
Cast iron	I	x										x						x	x	x				x	x
	M	x	x	x	x							x						x	x	x				x	x
	T	x	x	x	x							x						x						x	x
		x	x	x	x								x						x						x
Nickel and alloys	S	x		x		x	x			x	x	x			x	x	x	x	x	x	x	x	x	x	x
	I	x	x	x		x	x			x	x			x	x	x	x	x	x				x	x	
	M	x	x	x			x				x			x	x	x	x	x					x	x	
	T	x		x				x			x			x	x			x					x	x	
Aluminum and alloys	S	x	x	x		x	x			x	x			x	x	x	x	x		x	x		x	x	
	I	x		x		x	x				x			x	x	x				x	x				
	M	x		x			x				x			x	x	x				x					
	T			x							x			x	x						x				
Titanium and alloys	S			x		x	x			x	x		x		x	x		x	x				x	x	
	I			x		x	x				x		x	x		x		x					x	x	
	M			x		x	x				x		x	x		x		x					x	x	
	T			x			x				x		x		x	x		x					x	x	
Copper and alloys	S			x		x	x			x†	x				x		x	x	x	x	x		x	x	
	I			x						x				x				x			x		x	x	
	M			x						x				x				x					x	x	
	T			x						x				x				x					x	x	
Magnesium and alloys	S			x		x				x					x	x	x	x			x		x		
	I			x		x				x				x	x	x	x				x		x		
	M			x										x	x	x					x		x		
	T			x											x								x		
Refractory alloys	S			x		x	x			x	x				x		x	x	x	x		x	x		
	I						x			x	x				x		x	x					x		
	M																								
	T																								

LEGEND

Process Code:

SMAW = shielded metal arc welding
SAW = submerged arc welding
GMAW = gas metal arc welding
FCAW = flux cored arc welding
GTAW = gas tungsten arc welding

PAW = plasma arc welding
ESW = electroslag welding
EGW = electrogas welding
RW = resistance welding
FW = flash welding

OFW = oxyfuel gas welding
DFW = diffusion welding
FRW = friction welding
EBW = electron beam welding
LBW = laser beam welding

TB = torch brazing
FB = furnace brazing
RB = resistance brazing
IB = induction brazing

DB = dip brazing
IRB = infrared brazing
DB = diffusion brazing
S = soldering

Thickness:

S = sheet: up to 3 mm (1/8 in.) I = intermediate: 3 to 6 mm (1/8 to 1/4 in.) M = medium: 6 to 19 mm (1/4 to 3/4 in.) T = thick: 19 mm (3/4 in. and up).

*Commercial process.

†Copper requires molybdenum-coated tips.

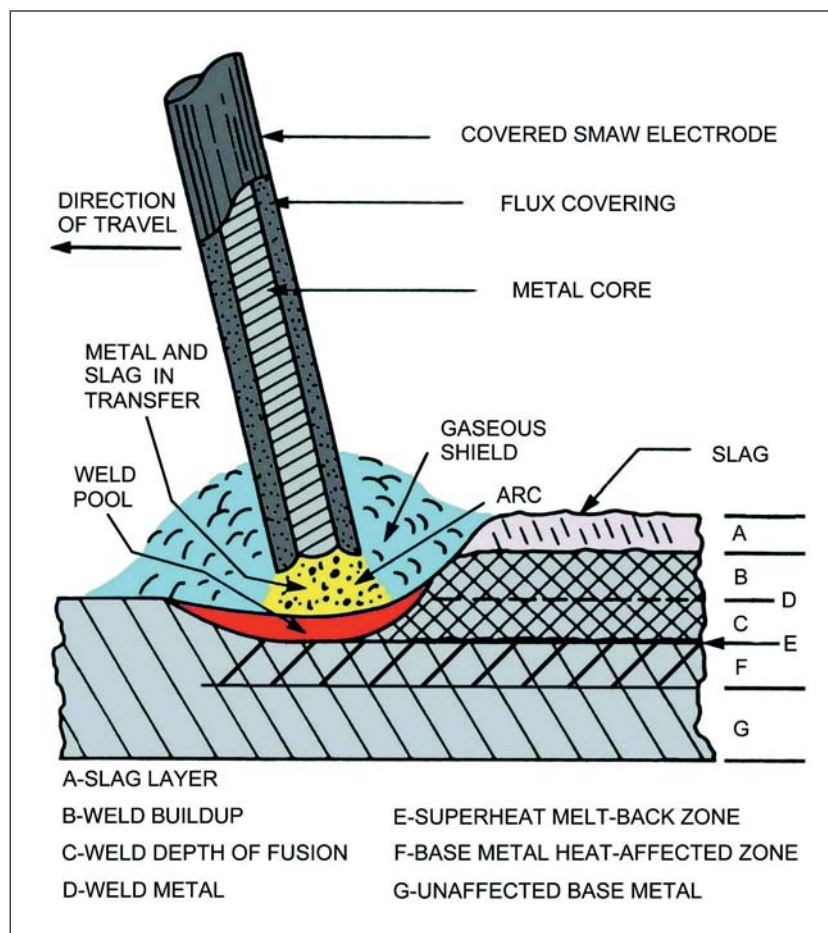
Shielded Metal Arc Welding

Illustrated in Figure 1.1, shielded metal arc welding (SMAW) is used to weld ferrous and some nonferrous metals. SMAW is sometimes referred to colloquially as *stick welding* or simply *arc welding*. This process incorporates the use of a metal arc (an arc that transfers metal) which is formed between a covered electrode and the weld pool. The electrode typically consists of a solid wire core around which a concentric flux mixture of silicate binders and powdered materials such as fluorides, carbonates, oxides, metal alloying elements, and cellulose is extruded. This covering serves as a source of arc stabilizers and vapors to displace air as well as metal

and slag to protect, support, and insulate the hot weld metal.⁶

The process name *shielded metal arc* could be used to describe a number of arc processes because most use some means of shielding to protect the molten weld pool. However, this term is unique to the process in which shielding is achieved by means of the decomposition of the coating on the electrode as it is consumed by the heat of the arc.

6. An excellent guide to the classification of SMAW electrodes is provided in the appendices of the applicable filler metal specifications. See, for example, American Welding Society (AWS) Committee on Filler Metals, *Specification for Covered Carbon Steel Electrodes for Shielded Metal Arc Welding*, AWS A5.1/A5.1M, Miami: American Welding Society.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.8.

Figure 1.1—Schematic Representation of Shielded Metal Arc Welding

The bare section of the electrode is clamped into an electrode holder, which is connected to the power source by a cable. The workpiece is connected to the other power source terminal. The arc is initiated by touching the tip of the electrode on the workpiece and then withdrawing it slightly, thus initiating the arc. The heat of the arc melts the base metal in the immediate area of the arc initiation along with the electrode's metal core and covering. The molten base metal, the wire core, and any metal powders in the covering coalesce to form the weld.

When arc welding was developed during the latter part of the nineteenth century, welding was more difficult due to the less-than-ideal electrical power sources available and the fact that a bare metal rod was used as the consumable electrode. This bare metal electrode made it very difficult to initiate and maintain an arc. Also, the bare electrode provided no protection from the atmosphere and the resulting weld had poor properties.

Flux coatings for welding electrodes were developed in the 1920s and have undergone improvements in terms of formulation and production since that time. These improvements have resulted in ease of arc initiation and operation as well as excellent weld properties. The ingredients in the coatings stabilize the arc by providing continual ionization of the arc column and they produce (1) shielding vapors, which displace air; (2) deoxidizers and other scavengers that purify the weld; (3) additional alloying elements; and (4) slag, which provides a physical protection or covering over the hot weld metal. Electrode coatings that incorporate powdered metal can increase the deposition rate and enable the operator to drag the electrode lightly on the coating instead of having to maintain a proper arc length manually. This tends to reduce operator fatigue, minimizes skill requirements, and often increases productivity.

Covered welding electrodes are available in diameters ranging from 1/16 inch (in.) to 5/16 in. (1.6 millimeters [mm] to 7.9 mm). The smaller diameters are used with low currents for the joining of thin sections, limited-access work, and welding in the vertical and overhead welding positions. The larger-diameter electrodes require higher currents, which produce higher weld deposition rates. With respect to economy, the goal is to use the electrode with the highest deposition rate and the highest current practical for the application.

In order to realize the economic potential of the larger electrodes, the amperage per square inch (in.²) (square millimeter [mm²]) of the electrode cross-sectional area, termed *current density*, must be optimized. Although electrodes can function at a significantly lower current density than the optimum setting, a low current density decreases productivity. Weld deposition rates vary directly in relation to the current density used. Smaller electrodes cannot conduct currents as high as larger diameter electrodes, but they are able to

maintain a high current density. In many cases, small electrodes with higher current densities can yield higher deposition rates and deeper penetration than larger electrodes with lower current densities.

The application of the SMAW process involves relatively high labor costs due to lower process efficiency and the higher skilled labor required. This process yields a deposition efficiency of less than 60% based on a comparison of the weight of electrodes purchased to the weld weight obtained. This relatively low efficiency is due to several factors. These include the discarding of electrode stubs when the electrode is consumed to within 2 in. to 3 in. (50.8 mm to 76.2 mm) of the electrode holder or when a portion of the covering is knocked off. In addition, slag must be chipped from the completed weld. Compared to the wire-feed arc processes, the labor costs of the shielded metal arc process are high due to its slower deposition rates, higher degree of skill required, time loss associated with changing electrodes, and the removal of the slag from the weld after each pass.

The equipment used in SMAW is the simplest and least expensive of that used for the electric welding processes. The necessary components are a power source of adequate current rating and duty cycle, suitably sized electrical cables, an electrode holder, and a workpiece-lead clamp. Utility-duty, single-phase alternating-current (AC) welding machines are the least expensive and can be used with small electrodes designed for AC current. Industrial-duty alternating current/direct current (AC/DC) or DC power sources can be used with the greatest variety of electrodes. Engine-driven portable machines with a wide range of capabilities are marketed at various prices, depending on the polarity and power output options desired.

With respect to personal protective equipment, SMAW operators must wear sturdy dry clothing and leather gloves for protection against spatter and electric shock. A helmet should be equipped with a dark lens (shade number 10 or higher recommended for most applications) that shields the eyes from the brilliance of the arc, electromagnetic radiation, and flying slag particles or weld spatter.

The SMAW process offers several advantages in addition to the simplicity, low cost, and portability of SMAW equipment. With this process, shops can handle many welding applications using a wide variety of electrodes. Moreover, this process permits welds to be made in confined spaces. For these reasons, SMAW is used in the construction, pipeline, and maintenance industries, among others.

Disadvantages include low deposition rates, the inability to automate, and a higher level of skill to perform it. The need for frequent starts and stops creates conditions for cold laps, crater cracks, and similar problems if performed improperly.

Submerged Arc Welding

A versatile production welding process with high productivity, submerged arc welding (SAW) joins metals by heating them by an electric arc formed between a continuously fed, bare metal electrode that can be either a solid wire or cored wire and the workpiece. Illustrated in Figure 1.2, this process involves establishing and maintaining the welding arc submerged beneath a mound of granular flux particles. Additional flux is continually added in front of the electrode as welding progresses. The flux helps in stabilizing the arc, protecting the molten weld metal from contamination from the ambient atmosphere and may influence the chemical properties of the weld if an active flux is used. The arc quickly melts a portion of the flux and base metal but remains covered by a combination of melted and unmelted flux. Therefore, the arc generally cannot be seen because it is submerged under the flux and molten slag covering. When welding is completed, any unmelted flux is typically removed and can be reused after screening out any slag particles from it. Because some of the flux particles are damaged during recycling, typically reused flux is mixed in an even 50-50 mix ratio with fresh flux. The melted flux forms a slag cov-

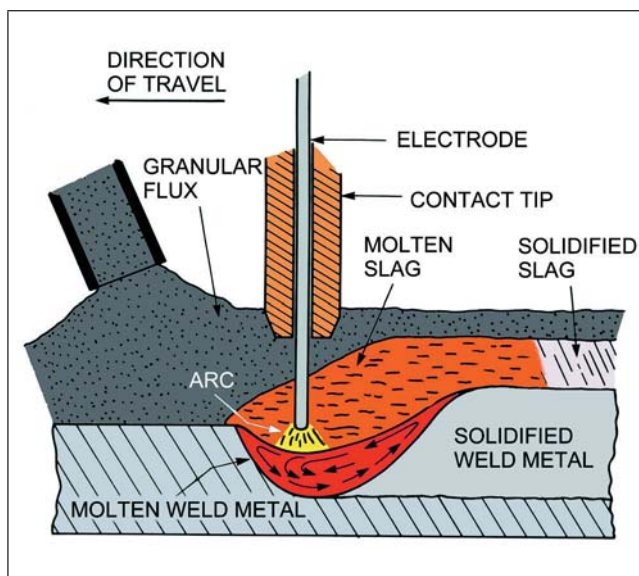
ering which must be removed after welding is complete or before any additional weld passes can be made.

Used extensively in pipe manufacturing, pressure vessel fabrication, bridge fabrication and ship-building, submerged arc welding is most widely employed in the welding of many grades of carbon and high strength low-alloy steels. Stainless steel and various nickel alloys are also effectively welded or used as surfacing filler metals with this process. Submerged arc welding is generally automated or robotic, though some industries still use manual or semi-automated application for short welds.

The welding positions best suited for submerged arc welding are the flat position for fillet (1F) and groove (1G) welds and the horizontal (2F) position for fillet welds. The welding of butt joints in the horizontal position (2G) can be accomplished but special flux shelves must be used to support the flux in the horizontal position for welding. Though rarely used, vertical welding has been done using a weaving technique with small diameter wires and specialized equipment. The overhead welding position cannot be utilized in submerged arc welding because the flux covering of the arc and molten pool cannot be maintained due to the effects of gravity.

The wire electrodes used in submerged arc welding are usually supplied in coils or drums. The electrodes can be either solid or tubular, composite wires. Some solid wires may be coated with a thin layer of Cu to improve the wire's corrosion resistance prior to welding and the current conduction during welding. For larger jobs, the larger-sized packages maximize economy by increasing operating efficiency and decreasing electrode unit costs. The electrode wire diameters usually specified in submerged arc welding range between 1/16 in. and 1/4 in. (1.6 mm and 6.4 mm). Due to the high current and deep penetration often used, this process is better suited to welding sections thicker than 1/4 in. (6.4 mm). However, reduced current and 3/64 in. (1.1 mm) or smaller electrode wire can be used for welding thicknesses below 1/4 in. (6.4 mm).

The flux used in submerged arc welding can be selected in combination with the electrode filler metal to yield specific weld properties. Various filler metal-flux combinations produce beneficial chemical reactions and modify the chemical composition of the weld metal. The unmelted flux can be vacuumed from the completed weld and reused once any lumps of slag have been removed through sifting. The reused flux is typically mixed in equal proportions to new flux because the flux particles can become mechanically damaged during the recycling process which can produce too many particle fines. Magnets are often used during sifting to remove any unwanted mill scale or other metallic particles. The melted flux leaves a slag deposit that is easily removed, leaving a bright, clean, smooth weld with no spatter.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.18.

Figure 1.2—Schematic of Submerged Arc Welding

However, flux in the area of the weld joint tends to slow the cooling rate of the weld and the adjacent base metal after welding. This effect may impact the hardness profile of the heat-affected zone (HAZ) depending on the chemistry of the base metal and the actual rate of cooling in the HAZ. This may not be acceptable for metal alloys that require high toughness values or for materials that require a faster cooling rate to minimize the HAZ degradation of a tempering treatment. Adjustments to the procedure, such as decreasing the amperage and voltage or increasing the travel speed can help to decrease the heat input and its impact on the HAZ. The common formula for determine heat input for non-waveform power supplies is shown below.

Heat Input (Joules) =

$$\frac{\text{Arc Voltage} \times \text{Welding Current}}{\text{Travel Speed}} \times 60$$

High current densities are possible with submerged arc welding because the flux has a stabilizing effect on the arc. High current densities yield high deposition rates and deep penetration. The deep penetration can minimize the amount of joint preparation required, though the depth-to-width ratio of the weld may be critical in some alloys to prevent centerline cracking in the weld. The high deposition rate and deep penetration result in a high level of productivity. Figure 1.3 illustrates this type of joint.

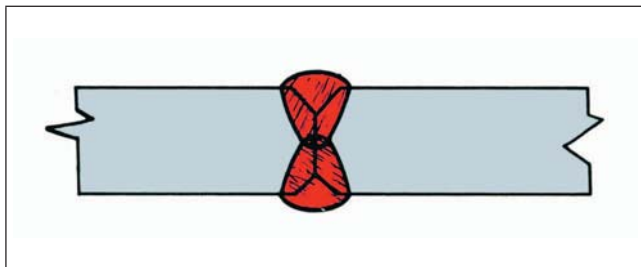
With submerged arc welding, electrical parameters and the travel speed along the joint can be adjusted to produce a variety of weld profiles, ranging from a wide, flat deposit with little penetration to a deep, narrow weld with a high bead reinforcement or buildup. Alternating current, direct current electrode positive (DCEP) and direct current electrode negative (DCEN) can be used to change to resulting profile of the weld.

Though single-electrode welding is the most common configuration used in submerged arc welding, a

combination of multiple electrodes and cold wires (wires not heated by another source) can be used to achieve a higher productivity and penetration control. When two wires with separate power sources are used in SAW, it is referred to as a tandem arc process. A typical SAW tandem arc procedure utilizes DCEP for the first electrode and ac for the second electrode. Deep penetration into the joint root face is achieved by using DCEP on the first electrode, while higher deposition rates and minimal arc blow (deflection of the arc from its axial path due to the effects of magnetic fields) are achieved using AC on the second electrode because it disrupts the continuous flow of the DC magnetic flux fields due to the constant polarity changes. The tandem arc process is typically used to join thicker base metals. As many as five electrodes feeding into the same weld pool can be used. Submerged arc welding can also be performed with a metal strip-type electrode for surfacing applications. This results in a wide deposit with minimal penetration and a high deposition rate.

With no visible arc and very little smoke or fume generation, submerged arc welding offers advantages with respect to environmental safety concerns. Operators need not wear a helmet or heavy protective clothing, though eye protection must be worn to shield against unexpected hazards. Hand protection should be used for handling hot slag and the weldment. Special care should be taken when pouring or otherwise handling flux to avoid breathing the dust that is generated. Because certain elements can be hazardous when vaporized, the manufacturer's safety data sheets (SDSs) should be consulted to identify potentially hazardous materials.

In summary, the main advantages of submerged arc welding are high deposition rates, alloy combinations available, and weld process stability. The main disadvantages are that the process is typically limited in the positions for which it can be used, the flux must be properly stored and maintained, the flux must be reprocessed for reuse, the process cannot typically be used on thin materials and there is a slag waste component which must be addressed.



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.44.

Figure 1.3—Joint with Thick Root Face

Gas Tungsten Arc Welding

The gas tungsten arc welding (GTAW) process, sometimes referred to colloquially as *TIG welding*, incorporates the use of a nonconsumable tungsten electrode to initiate and sustain the arc, which is shielded from the atmosphere by externally supplied gas. The gas is almost always inert, but there are cases where an active gas can be used for very specialized applications. Gas tungsten arc welding is the one of most versatile of the arc welding processes. Welds can be made with or without filler metal and the process can be used to weld very thin materials that are just a few thousandths of an

inch (less than 1 millimeter) thick. Gas tungsten arc welding can be used in all welding positions to join just about all weldable ferrous and nonferrous alloys. Internationally, the gas tungsten arc process may also be referred to as TIG—tungsten inert gas or WIG—Wolfram (the chemical element name of tungsten) inert gas. The process may also be called TAG if the shielding gas contains an active component such as an addition of nitrogen or hydrogen.

Gas tungsten arc welding can be used in automated or robotic applications, but is most often used in manual applications. Weld control is excellent in gas tungsten arc welding because voltage can be controlled by the length of the arc, current can be adjusted via welder or automated controls, wire feed is independent of the other variables and travel speed can be varied as required. This excellent control yields exceptional fusion and wetting at the beginning of the weld, thus avoiding incomplete fusion, which can take place when using consumable electrode processes. Figure 1.4 illustrates the gas tungsten arc process.

The shielding gas utilized in gas tungsten arc welding is almost always completely inert. Argon is the predominant shielding gas used, though helium and argon-helium mixtures are sometimes utilized to increase weld penetration. Inert gas shielding displaces the ambient atmosphere so that welding can take place in a nonreactive atmosphere. Reactive gases such as hydrogen or nitrogen are sometimes mixed with the inert gas to obtain specialized effects (example: oxides on 300 series stainless steels are reduced on due to the effects of hydrogen) or to increase productivity. The use of active

gases is very limited in industry and used only for very special applications. Because the tungsten electrode may react unfavorably with certain shielding gases, the overall number of shielding gases that can be used with this process is limited.

Tungsten electrodes are often alloyed with small amounts of oxides of lanthanum, thorium, or cerium. These oxide additions enhance the electron emission of the electrode and can also raise the melting temperature of the electrode which enables the electrode to be used at a higher current level without inducing melting. The American Welding Society (AWS) standard *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M,⁷ contains specifications for the tungsten electrodes used in gas tungsten arc welding.

The selection of a power source for gas tungsten arc welding is based on the polarity of the welding current required for the base metal, current level required and any additional equipment features desired such as pulsation. Some power sources are capable of producing square-wave AC, which renders better arc performance than the conventional sine-wave AC. Some power sources have a pulsed-arc option. A pulsed arc first supplies a higher current pulse to the arc to achieve thorough fusion; a lower current pulse is subsequently supplied to prevent the electrode from overheating and melting. This lower current also prevents excessive melting of the base metal. Pulsed-arc current allows adjustments of the pulse current time, background current time, peak current level, and background current level to enable the creation of tailored wave forms that are best suited for particular applications.

The choice of polarity is important with direct current because the direction of current flow changes the how the thermal energy is distributed in the arc. DCEP heats the electrode much more than DCEN; thus, DCEP is rarely used except for very thin materials or for surfacing. When welding metals that have refractory oxide surfaces, such as aluminum and magnesium, oxide cleaning can take place in the electrode positive portion of the AC cycle because current flows from the base metal to the tungsten.

Some gas tungsten arc welding power sources also permit polarity adjustments. Adjustable polarity enables the modification of the alternating current in two ways—either by changing the proportion of time duration in the desired polarity, either electrode positive or electrode negative, or by adjusting the amplitude of the current in the desired direction. The greater the adjustment in the electrode positive current direction, the greater the oxide cleaning effected. It should be

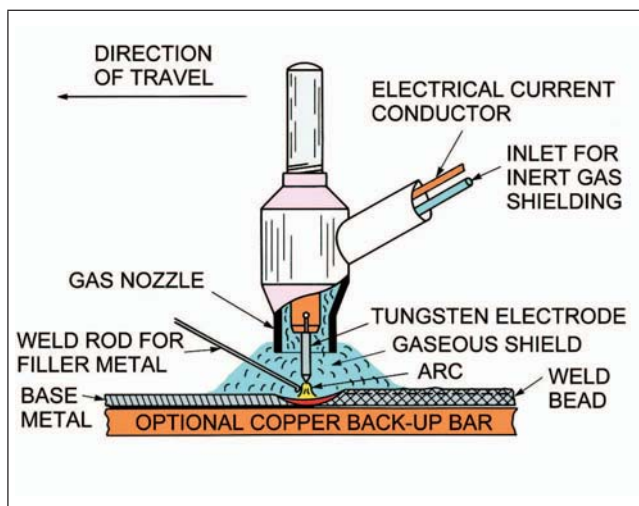


Figure 1.4—Schematic Representation of Gas Tungsten Arc Welding

7. American Welding Society (AWS) Committee on Filler Metals, *Specification for Tungsten and Tungsten Alloy Electrodes for Arc Welding and Cutting*, AWS A5.12/A5.12M, Miami: American Welding Society.

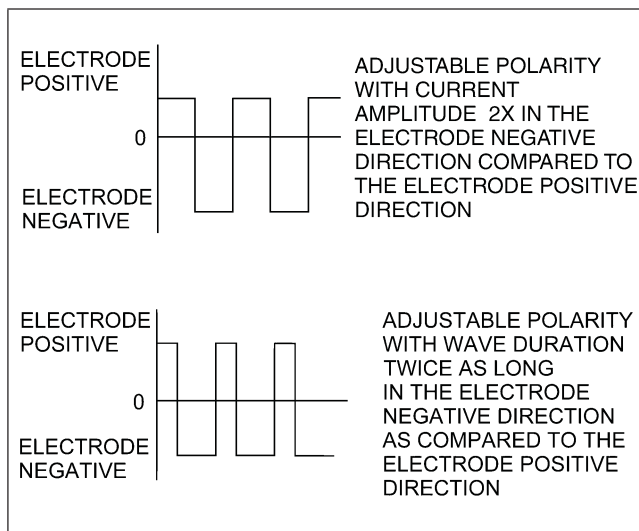


Figure 1.5—Square-Wave Alternating Current Adjustable Polarity Options

noted that polarity adjustments also result in additional heating of the tungsten electrode. Figure 1.5 illustrates these adjustable polarity options. Some newer power supplies have the ability to change frequencies of the alternating current cycle which can be used for multiple purposes and effects.

Gas tungsten arc welding can be done both with and without the addition of filler metal. Welds that are made without filler metal are called autogenous welds. For nonautogenous welding, filler metal can be added either manually or mechanically into the pool, where it is melted by the thermal energy of the molten pool. Care must be taken not to allow the filler metal rod to come into direct contact with the electrode, which would cause some of the filler to melt onto the tungsten electrode resulting in contamination. Techniques known as *hot-wire feed* and *cold-wire feed* are options of the mechanical feeding method. The hot-wire feed method involves preheating the filler metal through an external power source to minimize the thermal energy required by the molten weld pool to melt the filler metal, while the cold-wire technique involves no separate heating of the filler metal. The hot wire feed method increases the productivity of the process by increasing the deposition rate more than the cold-wire feed method.

A disadvantage of gas tungsten arc welding is its low relative productivity due to the lower travel speeds and deposition rates. Also, gas tungsten arc welding requires more skill, especially when manually feeding the filler

metal, as both the torch and filler metal must be coordinated simultaneously. Mechanical wire feeding systems decrease the required skill level and somewhat increase process productivity.

The primary advantage of the GTAW process is its capability to join a wide variety of materials. Additionally, the process tends to be very stable and there is a greater control over heat input than with other welding processes resulting in an improved suitability for use on very thin materials. With respect to other arc processes, it is also easier to make radiographically clear welds.

Plasma Arc Welding

Plasma arc welding (PAW), illustrated in Figure 1.6, produces welds by striking a constricted arc between a nonconsumable electrode and the weld pool (transferred arc) or between the electrode and the constricting nozzle (nontransferred arc). The PAW process is very similar to the GTAW process, as it was a technological advancement based on the GTAW process. The process uses an inert shielding gas for almost all applications. Plasma arc welding lends itself to automated and robotic welding.

Though classified as a gas shielded arc process, plasma arc welding functions like a high power density process, as it has the capacity to join materials with the keyhole welding technique (see below) along with the conventional melt-in welding method (i.e., involving weld pools). A tungsten electrode is recessed in a nozzle that has a very small orifice through which the arc/gas plasma has been heated to an ionized condition, allowing the resulting plasma to carry electric current. This constricted orifice concentrates the arc and increases the exit velocity resulting in a well-defined, high power density plasma column. It is this aspect of the arc that makes the process function similar to a high-power-density process such as laser welding or electron beam welding. The PAW arc is stiffer and more stable than that used in gas tungsten arc welding because of the high velocity at which the plasma is propelled from the torch towards the workpiece. Thus, the PAW arc is less sensitive to the torch stand-off distance which is the distance between the nozzle and joint.

As illustrated in Figure 1.6, in both the transferred arc and nontransferred arc process variations, the tungsten electrode is connected to the negative terminal of the power supply. The positive terminal is connected to the workpiece in the transferred arc mode but it is connected to the orifice nozzle in the nontransferred arc variation. The constricted orifice concentrates the heat by producing a plasma jet with temperatures in the range of 30 000°F to 50 000°F (16 650°C to 27 760°C). This temperature is much higher than a typical open arc process which typically range from

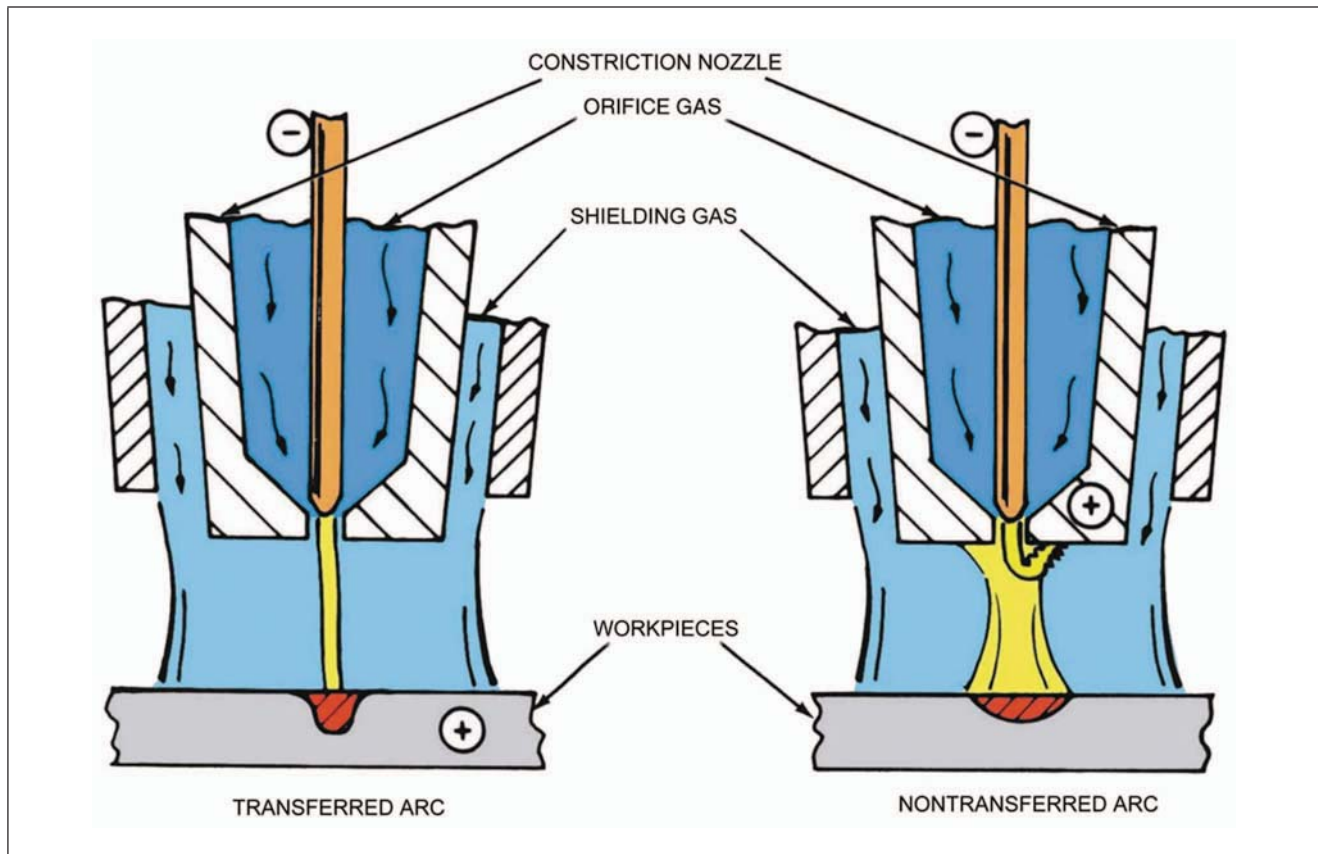


**Figure 1.6—Schematic Illustration of Plasma Arc Welding:
Transferred Arc (Left); Nontransferred Arc (Right)**

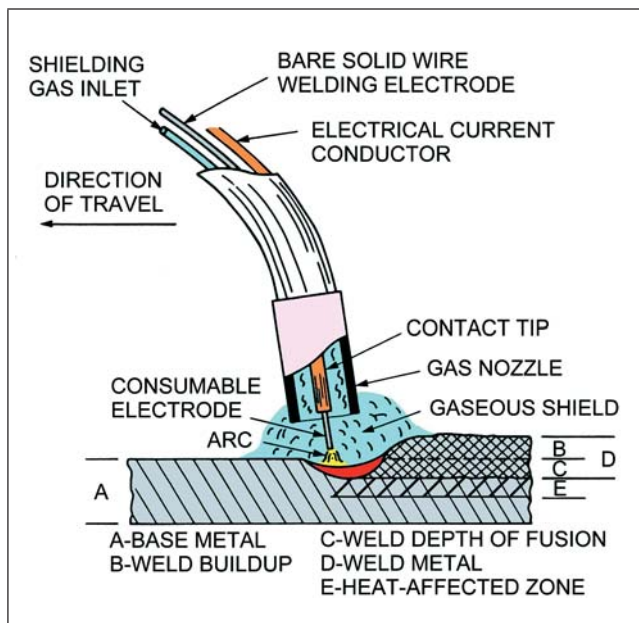
9000°F to 10 000°F (4980°C to 5540°C). Therefore, keyhole welding is possible in metal thicknesses up to 1/2 in. (12.7 mm) when implementing transferred arc plasma arc welding on a tightly fitted square butt joint. Thicker materials can be welded using the keyhole method when combined with a V- or U-groove through a portion of the joint thickness.

The keyhole technique results in excellent productivity because a high travel speed is required to maintain a stable keyhole. The high travel speed requires mechanization, precise joint location, and fit-up. In contrast, nontransferred arc plasma arc welding is used mostly for melt-in welding techniques, surfacing, and thermal spraying applications. It lends itself to manual control in many instances.

A low-power version of plasma arc welding, sometimes referred to as *microplasma arc welding*, is capable of welding materials as thin as 0.001 in. (0.025 mm). Much of this type of welding can easily be done manually.

Gas Metal Arc Welding

Gas metal arc welding (GMAW), often referred to colloquially as *MIG*, involves the use of an arc and consumable electrode with externally added shielding gas. In other parts of the world, the welding process is called MIG for metal inert gas, or MAG for metal active gas depending on the composition of the shielding gases used. With the various choices of metal transfer modes through the arc described below, the wide range of electrode sizes available, and the numerous shielding gas mixtures possible, the GMAW process can be used to weld many ferrous and nonferrous metals. These metals can range in size from 0.020 in. (0.51 mm) thin-gauge sections to any desired plate or pipe section thickness. With the proper procedure and technique, gas metal arc welding can be performed in all positions. If the variables are properly set on the controls of the welding machine then less skill is typically required for gas metal arc welding than for the SMAW or GTAW pro-



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.12.

Figure 1.7—Schematic Representation of Gas Metal Arc Welding

cesses. Figure 1.7 illustrates the gas metal arc welding process.

The shielding gas or gas mixtures used in gas metal arc welding are not completely inert unless welding aluminum or magnesium. Shielding gas generally consists of carbon dioxide, argon-carbon dioxide mixtures, argon-oxygen mixtures, or multiple gas blends. The mixed shielding gas blends typically result in smoother arc performance, less spatter, and promote enhanced wetting of the weld to the base metal. Most mixtures have been standardized and are commercially available in cylinders or bulk gas systems.

Gas metal arc welding employs either a solid electrode wire or an electrode with a core of powdered metal. A variety of ferrous and nonferrous alloys are available. Electrode sizes range from 0.020 in. to 0.062 in. (0.5 mm to 1.6 mm). Spool weights can vary from 1 lb to 60 lbs (0.5 kg to 27 kg), coils weigh from 50 lbs to 65 lbs (23 kg to 29.5 kg), and drums or bulk reels can weigh as much as 1000 lbs (450 kg). The unit cost of electrode wire usually varies inversely with the size of electrode and the weight of the spool, coil, or drum purchased. For example, the unit cost of a given alloy of 0.020 in. (0.5 mm) wire on a 1 lb (0.5 kg) spool may be

more than five times higher than the unit cost of 0.062 in. (1.6 mm) wire purchased in a 1000 lbs (450 kg) drum. It is economically advisable to use the largest-sized electrode wire wound on the largest-sized spool, coil, or drum practical for the application.

One significant variable in any wire-fed arc process is the electrical stick out which is the distance between the contact tip and the work. This distance includes the length of wire extension past the contact tip as well as the height of the welding arc. The electrode is a very small conductor and therefore has high electrical resistance. The sensitivity to the effects of electrical stick out is affected by the bulk resistivity of the wire. Nickel and stainless steels have higher resistivity than aluminum and so the effect of the electrical stick out will be increased. If the extension of the electrode increases in a constant-voltage system, the current decreases rapidly because more current is used to preheat the electrode through resistive heating. The current is a function of wire feed speed and electrode extension. The current varies directly with wire feed speed but inversely with extension. However, deposition rate is a function of wire feed speed only because it is based on weld volume applied over time. If the wire feed is constant, the deposition rate is constant even though the current changes as the extension changes.

The basic equipment and accessories used in gas metal arc welding include a welding gun (air or water cooled); wire electrode; wire feeder; a power supply; shielding gas; cables and hoses; and in the case of water-cooled torches, a water circulation system. This process lends itself well to semiautomatic (manual), fully mechanized, automatic, and robotic welding. In semimechanized welding, the operator holds the welding gun, controlling the torch angles, extension, and travel speed along the joint. Alternatively, the gun can be mounted on a carriage with an adjustable speed control and moved along the joint at the desired travel speed.⁸

Several types of metal transfer variations can be used in gas metal arc welding, depending on a number of factors. These variations include the spray, globular, short-circuiting, pulsed-arc, and high-deposition, buried-arc metal transfer modes. Figure 1.8 summarizes these arc modes as a function of current density, illustrating their respective positions relative to one another. The type of shielding gas used also affects the metal transfer modes. For example, when using carbon dioxide, the resulting metal transfer is either short circuiting mode at lower current densities or the globular transfer mode at high current densities. True spray transfer mode cannot typically be achieved with 100% carbon dioxide shielding gas. The larger the electrode used, the higher the current required for a given current density.

8. For more information, see Chapter 9 of this volume.

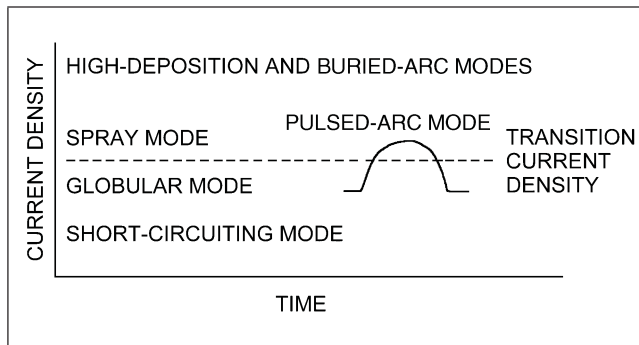
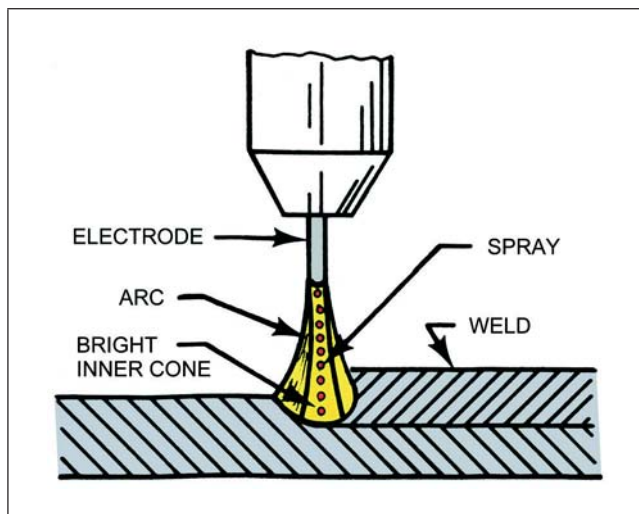


Figure 1.8—Gas Metal Arc Welding Transfer Mode Comparison

When the current density is increased above a point defined as the transition current density level, spray transfer mode is achieved. In spray transfer arc mode, the electrode metal is transferred as tiny droplets across a stiff, stable arc, as illustrated in Figure 1.9. The stable arc produces very little spatter. Argon should be predominant in the shielding gas mixture. Because this mode produces a high volume of molten metal at a high rate of speed, spray transfer is typically considered suitable for the flat and horizontal positions when using conventional CV power supplies. When using pulsed GMAW, spray metal transfer mode can sometimes be used in other welding positions.



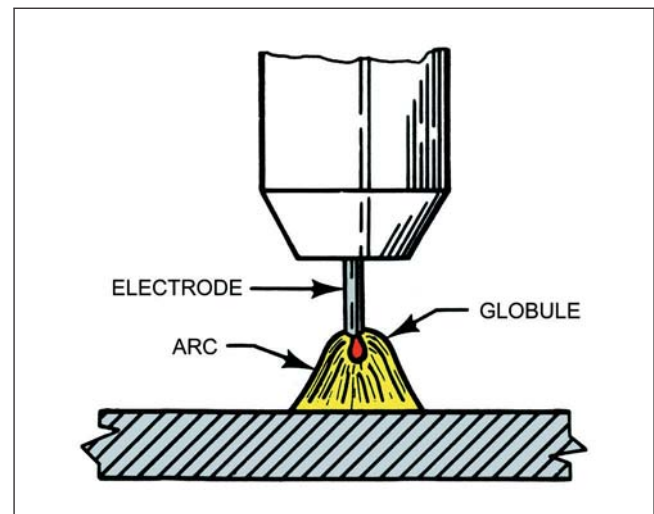
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.26.

Figure 1.9—Schematic Illustration of Spray Metal Transfer

Globular transfer mode, shown in Figure 1.10, is obtained when the current density is just below the transition current density level. When carbon dioxide is used as the shielding gas, globular transfer occurs even at high current density. The metal droplets formed at the end of electrode are larger in diameter than the electrode itself. With solid electrode wire, globular mode produces a rather erratic arc. In this case, the metal globules are propelled from randomly varying positions with respect to the center of the electrode tip. Substantial spatter results, producing a weld deposit that is rough and uneven. A more controlled version of this mode is used in flux cored arc welding (FCAW), an arc welding process using an arc between a continuous filler metal electrode and the weld pool. The process is used with shielding gas from a flux contained within the tubular electrode, with or without additional shielding from an externally supplied gas, and without the application of pressure (refer to the section on flux cored welding).

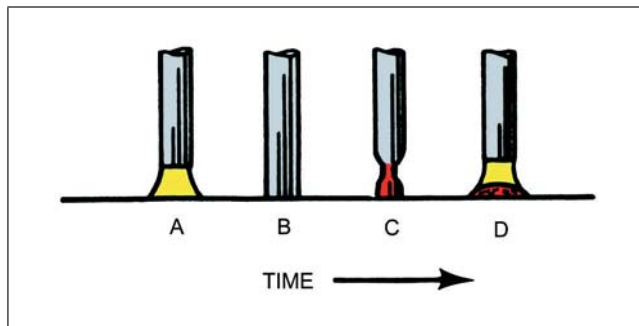
Short-circuiting transfer mode, which produces a characteristic crackling sound during welding, is obtained at the lowest range of current densities. The shielding gas mixture used in this mode, which can be applied in all welding positions, is typically rich in argon but can be 100% CO₂. It produces small, quickly solidifying welds suited to joining thin materials or bridging small root openings. In the latter case, this mode provides complete penetration and fusion to both members on the reverse side of an open root butt joint.

Figure 1.11 illustrates the short-circuiting metal transfer cycle. Position A shows the electrode prior to short cir-



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.28.

Figure 1.10—Gas Metal Arc Welding: Globular Metal Transfer Mode



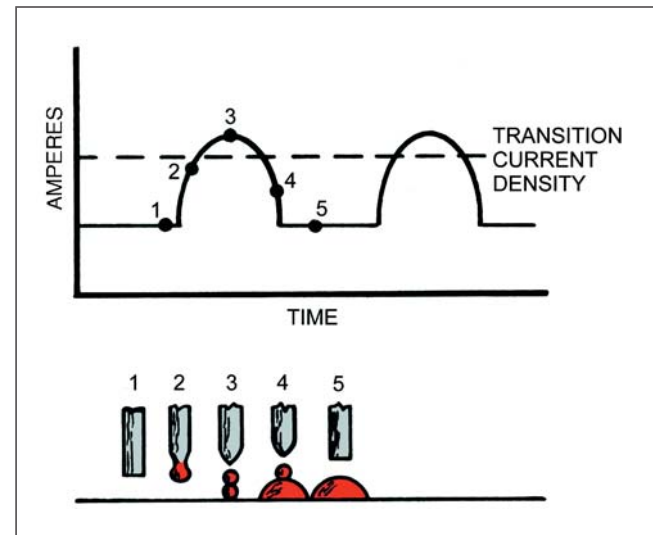
Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.30.

**Figure 1.11—Gas Metal Arc Welding:
Short-Circuiting Metal Transfer Mode**

cutting. The wire should be starting to melt prior to short circuiting and the droplet size should not be much greater than the diameter of the wire. Position B depicts the electrode short-circuiting to the weld pool, extinguishing the arc for an instant. Although this is not perceptible to the unaided eye, high-speed film has proven that the arc does indeed extinguish. Because of the short circuit, the globule is pinched off as the current peaks, as shown in position C. Position D shows the arc restored. This cycle can occur up to 200 times per second, depending on the electrical current and the shielding gas type used.

An important precaution must be observed when implementing the short-circuiting arc mode. Sufficient power must be used to obtain adequate fusion. For purposes of illustration, assume that a welder working with a section thicker than 1/4 in. (6.4 mm) is attempting to make a T-joint fillet weld traveling downhill using a 0.035 in. (0.9 mm) electrode at less than 100 A and 18 volts (V). The arc may sound as though it is working well under these operating conditions, but little if any fusion to the base metal is actually taking place because of insufficient power. Properly designed welding procedures must be carefully followed when operating in this mode.

Pulsed arc metal transfer mode (GMAW-P) is a metal transfer variation in which the welding current is pulsed. Shielding gases are generally composed of 90% or greater argon with a small addition of either CO₂ or oxygen. Figure 1.12 illustrates the behavior dynamics of the current with this mode. In Position 1, a low-background current is applied, prompting the formation of a small globule on the electrode. In Position 2, a pulse of current is about to cause the globule to separate from the electrode. In Position 3, the current has pulsed above the transition current density, and the droplet is transferred in spray metal transfer mode. The spray arc also



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.30.

**Figure 1.12—Gas Metal Arc Welding:
Pulsed-Arc Mode**

applies heat, which aids fusion. In Positions 4 and 5, the current density is returning to the background current.

The advantages of the pulsed-arc mode include the option of using larger electrode sizes, greater process productivity, and enhanced fusion with a greater base metal mass (as compared to the short-circuiting mode). The pulsed-arc mode can also be used in all positions. However, GMAW pulsed-arc equipment is much more expensive than that used for the other arc modes. In addition, pulsed-arc background and peaking current amplitudes and durations must be properly adjusted for the electrode alloy type and size being used with a given shielding gas. Various manufacturers offer synergic systems using inverter power sources. Several pulsed-arc systems have microprocessor controls to synchronize the variables. A number of factory preset program options may be included. To improve performance during particular applications, provisions for changing any of the preset parameters are also available.

As illustrated (refer to Figure 1.8), the two metal transfer modes having the greatest current density are the buried-arc mode and the high-deposition-rate mode. The current densities of these modes may exceed 300 000 A/in.² (465 A/mm²) of the electrode cross-sectional area. At these densities, a 0.045 in. (1.1 mm) electrode feeds at about 1500 in./min (38 meters [m]/min). The voltage used in buried-arc mode is low enough to permit the arc to be below the surface of the

metal, which produces a narrow, deep weld profile with a high crown or buildup. The high-deposition-rate mode utilizes a higher voltage, creating a wider weld profile that has less weld crown and is not as deep. The buried-arc and high-deposition-rate modes are normally implemented in fully mechanized or automatic gas metal arc welding.

Pulsed GMAW is no longer limited to the spray transfer mode. Computer technology and sensors have been developed to closely monitor the short circuiting process and respond dynamically to the process in near real time. For example, when a short circuit occurs, the current begins to increase due to the constant voltage power supply. In a standard GMAW process the current would continue to increase as the wire begins to melt and neck down in cross sectional area. This eventually ends in an explosive event as the short circuit is cleared and the arc is reestablished. In the pulsed short circuit mode, the power is controlled such that just prior to the short circuit being cleared, the power is temporarily turned off and the droplet is drawn into the weld pool by surface tension.

Once the droplet has detached from the wire, the power is switched back on and the arc is reestablished. There are several variations as to how this welding process adaptation is accomplished. The controls, algorithms and sensors used are independently developed by each of the manufacturers of the power supplies. Advantages can include spatter reduction, lower heat input, the ability to weld thinner gages of materials and the ability to control penetration.

There are several major advantages of gas metal arc welding. Foremost, the process can be used on a very wide range of metals and metal thicknesses, and is easier to learn and control than some of the other arc welding processes. The process is, by nature of the solid electrode, a low hydrogen welding process. Furthermore, the productivity is high due to the high deposition rates, the process is economically efficient because most of the wire used in the process is directly incorporated into the weld, and there is no loss from fluxes or the stub loss associated with SMAW.

However, there are also disadvantages to the GMAW process. Because the shielding is done with externally supplied gas, the process is sensitive to wind and weld quality can be impacted, and the process is less portable than shielded metal arc welding. Also, the welding arc is exposed during the process and those who are welding or may be exposed to the arc need to be adequately protected from the light intensity and UV exposure.

Flux Cored Arc Welding

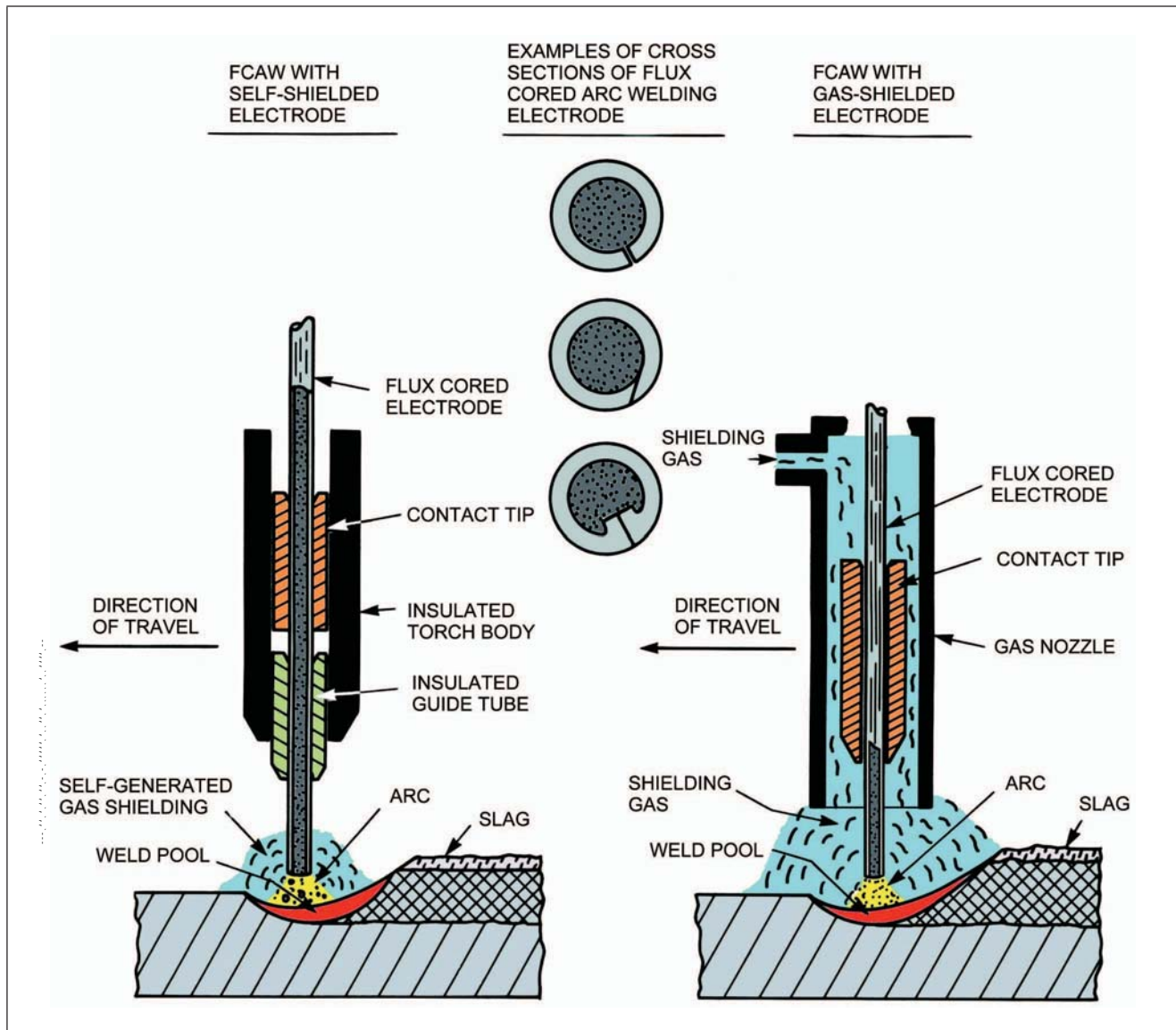
Flux cored arc welding (FCAW) uses the same type of power sources, wire feeders, and welding guns as gas metal arc welding. However, FCAW incorporates the

use of a tubular electrode with a core containing flux and alloying elements. A variation, self-shielded flux cored arc welding (FCAW-S), obtains its shielding gases from the breaking down of the internal flux component of the electrode as it is consumed by the arc. The FCAW-S gun differs from the GMAW gun in that it has no nozzle for shielding gas. Figure 1.13 illustrates both gas shielded and FCAW-S. Gas shielded flux cored arc welding (FCAW-G) is another variation of the process.

For self-shielded flux cored electrodes, the flux in the electrode core serves the same functions as the coating on the shielded metal arc electrode. It helps initiate and stabilize the arc and contains deoxidizers, additional alloying elements, scavengers, slag, and vapor-forming ingredients sufficient to provide necessary protection from the atmosphere. Self-shielded flux cored arc welding is suited to outdoor work in windy conditions in which externally added shielding gases would be blown away. Electrodes are marketed for carbon steels and some alloy steels. Gas-shielded flux cored arc electrodes must be supplemented by externally added gas, typically carbon dioxide. Electrode sizes range from less than 0.020 in. to 0.16 in. (0.5 mm to 4 mm).

The FCAW process can require more electrode extension than gas metal arc welding. If the extension is too short, the vapor-forming ingredients are not sufficiently heated to generate enough arc vapor for adequate shielding, potentially resulting in porosity in the weld. Some FCAW-S electrodes require even greater extension than FCAW-G electrodes.

Deposition rates in FCAW can be somewhat higher than those attained with gas metal arc welding in spite of less cross sectional area of the tubular wire when compared to the solid steel wire of the same diameter. With a given electrode size and current, the current density is also higher with flux cored electrodes than with the electrodes used for gas metal arc welding. This increased current density occurs because flux cored electrodes are tubular rather than solid, and the flux core is made up of metallic and nonmetallic ingredients that have a lower current-carrying capacity than solid metal. The slag ingredients have a protective effect on the molten weld pool because the molten slag floats on top of the molten metal. Some slag systems freeze prior to weld solidification while others solidify after the weld metal. Fast solidifying slags enable welding out of position because these slags act like a dam to hold the molten metal in place until it solidifies. The weld pool surface is typically very dynamic when this slag freezes and will result in a noticeable ripple pattern. The slower solidifying slags will result in welds with little to no ripple because the molten welds have an opportunity to calm some under the molten slag prior to the metal solidifying. The controlled globular transfer typical with FCAW allows for a broad range of electrical variables, which contributes to improved operating characteristics.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.17.

Figure 1.13—Schematic Representation of Flux Cored Arc Welding

The presence of flux as part of the process enables beneficial chemical reactions to occur, which are similar to the reaction of the coating ingredients on the SMAW electrode. However, the productivity potential is significantly higher than with SMAW due to the high current density used with this process and the fact that it is not necessary to stop to change electrodes. FCAW has a rather large window of operating variables as compared to gas metal arc welding, but the process efficiency is

lower than that in gas metal arc welding due to slag ingredients that aid in protection from the atmosphere but do not become weld metal. With the gas-shielded process, the shielding gas can be blown away by air drafts, as it would be with gas metal arc welding. However, with the self-shielded electrodes, protection from wind is similar to that of SMAW, allowing it to be used for outdoor applications. FCAW-G and FCAW-S can be used in automated or robotic welding.

The FCAW process has a wide range of applications. It is a versatile process utilized by fabrication shops for a variety of parts and products. It has the capacity to weld metals as thin as that used in vehicle bodies and as thick as heavy structural members of high-rise buildings.

There are several advantages of the FCAW process. Outdoor use is possible with self-shielded wires because no external shield gas is required. Wires have been developed to increase productivity for out of position welding due to higher deposition rates that are achievable with fast freezing slag systems. A wider range of weld compositions are achievable because the alloying load can be changed in the core composition. This allows for compositions that would be difficult to draw in a solid wire. Less welder skill is required than for GTAW or SMAW. The flux in the core composition may reduce the sensitivity to surface contamination on the parent metal to impact the weld quality.

The FCAW process has some disadvantages. There is a slag system which must be removed and discarded. Slag can get trapped as inclusions in the weld. Some core compositions are susceptible to hydrogen pick-up which can be a concern when welding some base metals. There is a greater likelihood of wire feeding issues with flux core welding wire than with solid welding wire.

Electrogas Welding

Electrogas welding (EGW), illustrated in Figure 1.14, is a mechanized arc welding process that utilizes either flux cored or solid electrodes. The shielding gas may be applied from an external source or produced by a flux cored electrode, or both. Electrogas welding has been used successfully on titanium and aluminum alloys in addition to steels. Though the process has relatively

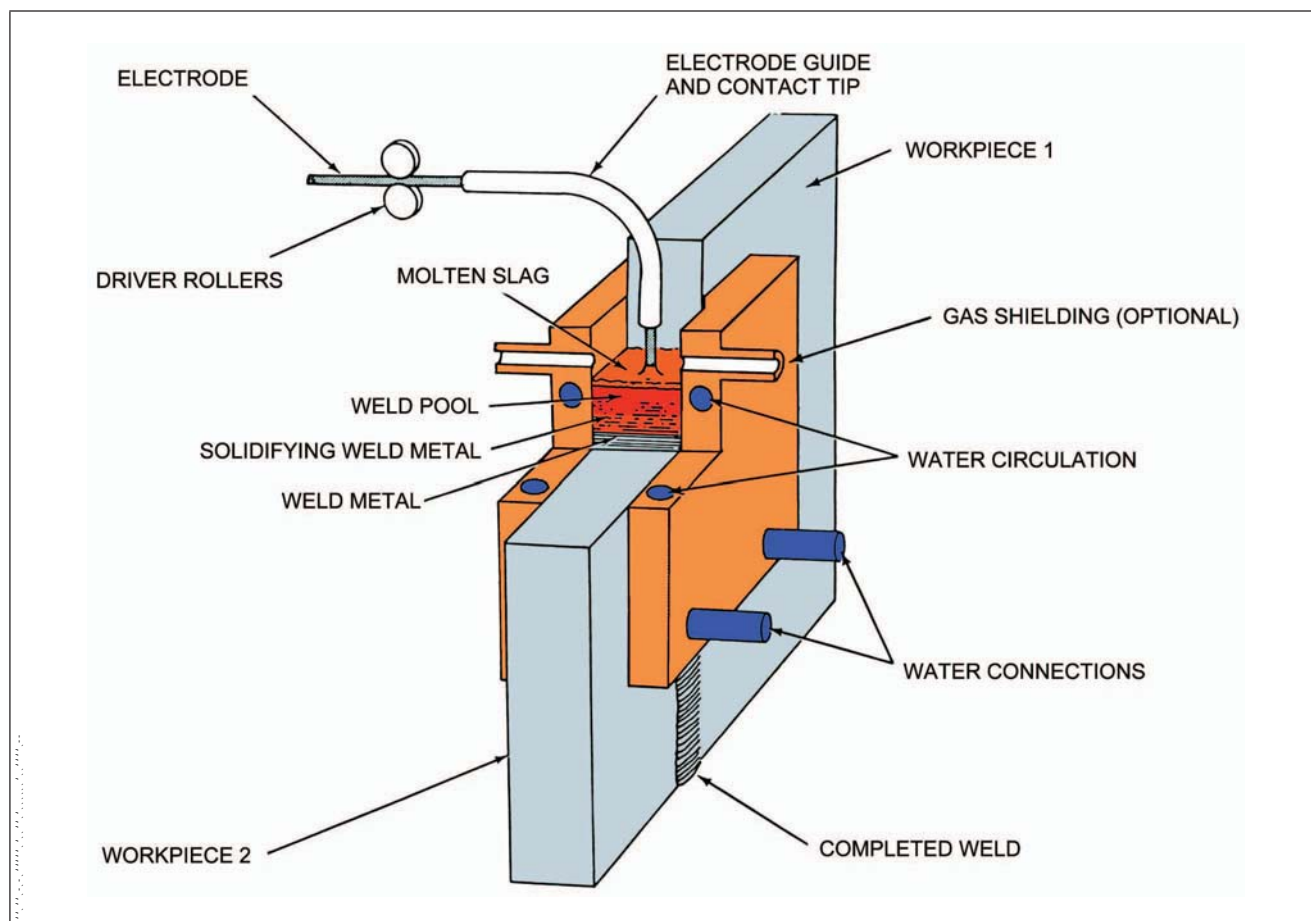


Figure 1.14—Schematic Representation of Electrogas Welding

limited use, it has been applied in the manufacture and repair of storage tanks, pressure vessels, ship hulls, and structural members.

The operation and applications of electrogas welding are similar to those used in electroslog welding, a high-energy-density process which is described in the section titled “Other Welding and Joining Processes.” Although these processes utilize different heating methods, both are used to weld thick sections in the vertical up position.

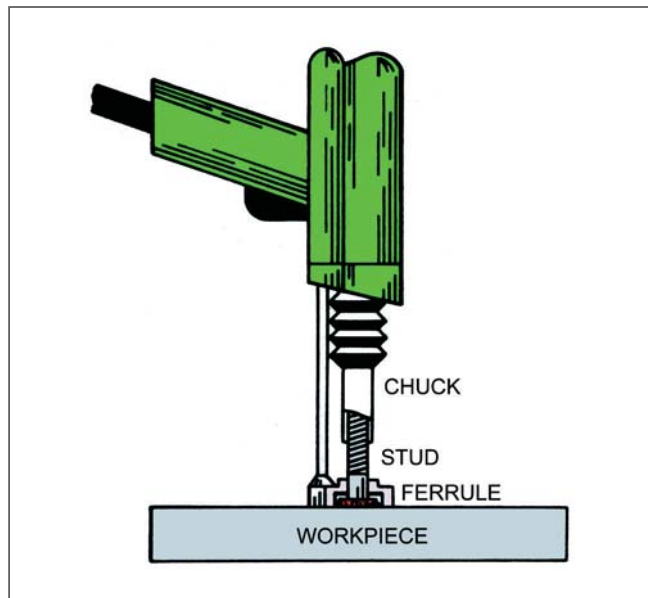
Electrogas welding machines vary in size from portable 75 lbs (35 kg) units that are usually self-propelled to the more commonly used massive machines that are moved by cranes from one weld joint to another. Both the lightweight and heavy units are typically used to weld sections 1/2 in. to 3 in. (12.7 mm to 76.2 mm) thick using a single electrode. To maintain constant arc voltage, the vertical movement of the welding head is usually automated, though other methods can be implemented. For circumferential welds, the welding head is fixed while the workpiece is rotated with the axis in the horizontal position.

The welding current used in this process depends on the electrode diameter and type. In general, EGW machines operate at amperages as high as 400 A with solid electrodes and as high as 750 A with flux cored electrodes. Deposition rates for these machines are typically 15 pounds per hour (lb/hr) to 30 lb/hr (7 kilograms per hour [kg/hr] to 13 kg/hr). Travel speed along the joint is governed by section thickness and deposition rate.

Electrogas welding has the capacity to produce square-groove and single-V butt joints. This process is also used for welding T-joints. Simple edge preparation for these standard joints minimizes joint preparation costs. Weld soundness is generally excellent, and because transverse shrinkage is uniform, the joints are essentially free of angular distortion. In addition, the use of high current density results in high deposition rates. Though this process offers both economic and quality benefits, it has extremely high heat input which can reduce overall weld mechanical properties due to excessive grain growth. Composite electrodes have been used with grain refining elements in the core which can be used to help reduce the large grain sizes that are exhibited by solid wire applications of this process.

Drawn Arc Stud Welding

Drawn arc stud welding (SW), illustrated in Figure 1.15, is a versatile electric arc welding process used to join innumerable devices—usually fasteners—to base metal. This process utilizes an electric arc struck between a metal stud and the workpiece and is applied without any additional filler metal and with or without shielding gas. Partial shielding may or may not be pro-

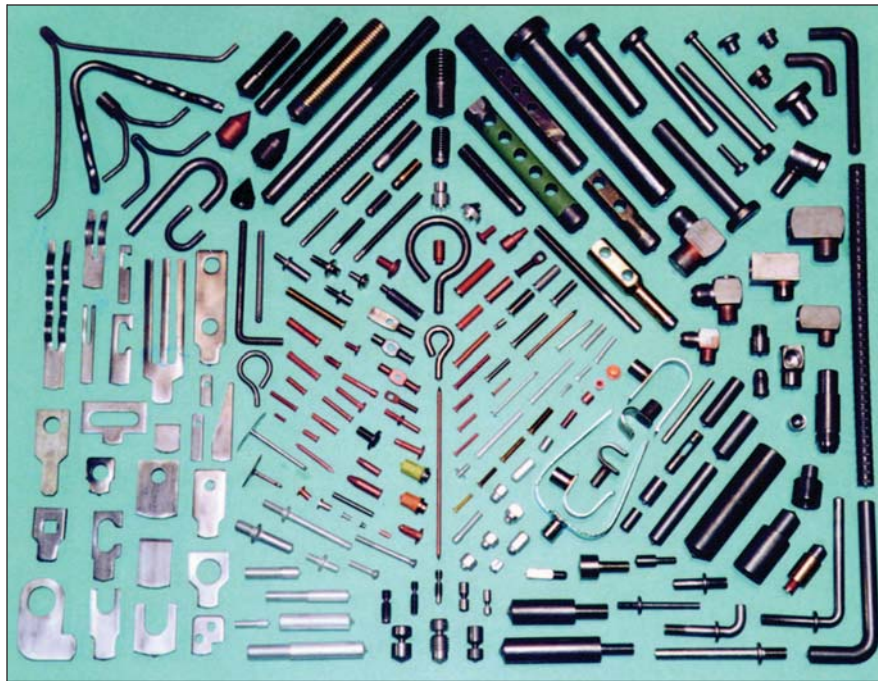


Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 5.63.

Figure 1.15—Schematic Representation of Stud Welding

vided by a graphite or ceramic ferrule surrounding the stud. Pressure is applied when the faying (closely fitting) surfaces are adequately heated. The process is typically completed in less than a second which makes this a highly productive process.

In manual arc stud welding, the stud and the graphite or ceramic ferrule are loaded into the chuck and held against the workpiece at the desired location. When the gun trigger is depressed, the stud is lifted, drawing an arc that is sustained for the prescribed length of time set on the timer. For a stud 3/8 in. (9.5 mm) in diameter, a typical arc time is 1/3 of a second (s). Most studs require less than 1 second of arc time. A molten pool forms on the workpiece and on the end of the stud. Then, as the current stops flowing, the stud is plunged into the workpiece, and the two pools coalesce and solidify. This creates a weld across the whole cross section of the stud, plus some excess. The graphite or serrated ceramic ferrule serves as a spacer and a physical shield. It is recessed to shape the excess weld metal and is removed after welding as a ceramic slag surrounding the weld. Deoxidation is accomplished with either an aluminum pellet or flux under a cap on the end of the stud. The aluminum pellet also is used as the arc initiator on large studs which do not get drawn back during



Photograph courtesy of Nelson Stud Welding®

Figure 1.16—Variety of Studs Commonly Used in Stud Welding

the welding process. Smaller studs have either an initiator tip that is cold headed on the stud or have a radius head to concentrate the energy which aids in arc initiation. Once the parameters for a given application are set, little skill is required to implement the process other than to maintain the stud angles and its dimensional location. Figure 1.16 illustrates a variety of available studs.

Studs smaller than 1/4 in. (6.4 mm) in diameter frequently use capacitor discharge energy because the welding time is only a few milliseconds. A graphite or ceramic ferrule is not used due to the extremely short arc time. Moreover, shielding methods are not required unless the metal oxidizes extremely quickly, such as aluminum. In this case, inert gas shielding, usually argon, is required.

The major advantages of stud welding are the minimal time and skill required for the operation. The process lends itself nicely to robotic welding. The process can be completely automated, or it can incorporate automatic stud loading to the gun with manual gun manipulation. Alternatively, the studs can be loaded manually into the gun. A limitation of the process involves the use of a brittle base metal, such as gray cast iron, in which weld metal shrinkage cannot be tolerated and HAZ cracking occurs.

RESISTANCE WELDING

Resistance welding (RW) encompasses a group of processes that effect the joining of faying surfaces with the heat obtained from the workpiece's resistance to the flow of welding current (Joule heating) and with the application of pressure. Shielding gases are not needed because air is squeezed out of the faying surfaces by the external force applied by the electrodes. Resistance welding processes are typically used when the product design specifies thin gauge materials that are to be joined in a lap joint configuration. Access to both sides of the weld is also required for the electrodes to apply force. Fully automatic and robotic systems are used for many of these applications, however, the process is still done manually in some cases.

Commonly implemented resistance welding processes are resistance spot welding (RSW), resistance seam welding (RSEW), resistance projection welding (RPW), and resistance stud welding. The main process variables associated with these resistance welding processes are welding current, welding time, electrode force, electrode material, and tip configuration. Once the parameters for these variables are properly adjusted, less skill is required to use the resistance welding processes than with other welding processes.

These four processes are frequently used in the joining of metals with individual sheet thicknesses of up to 3/16 in. (4.8 mm). Thicker materials can be welded, but they require much more force and higher welding current. This makes the processes less economical than other competing weld processes such as GMAW. In these processes, typically copper electrodes apply force to the lapped workpieces to be joined. The force of the electrodes on the outer surfaces of the parts to be joined squeezes out the air in the interface between the parts. The base metal is rapidly heated through resistive (Joule) heating. The heating occurs everywhere in the process that there is resistance; most heating occurs at the location in the circuit where the electrical resistance is the greatest. In other words, the electrical resistance must be greater at the interface between the two metals to be joined than between the electrode and base metal. It is essential that the metals to be joined have higher electrical resistance than the contact surface between the electrode and base material. The mechanical joints in the equipment must be maintained so that they do not cause resistances in areas other than the weld location.

A great deal of resistance welding is performed with single-phase AC current. Unfortunately, the very high welding current on a single phase yields a poor power factor. Another resistance welding variation uses very high three-phase DC output current for short durations. Though it does not directly impact the direct current used in welding, it does supply an excellent power factor to the manufacturing facility as the current load is balanced on all three phases. Yet another resistance welding approach utilizes the capacitor discharge method, which provides DC pulses as the capacitors discharge their store of electrical power. Although the total power requirement is relatively low in resistance welding, instantaneous power demand is very high. The electrical conductors must therefore be designed to carry the maximum kilovolt ampere (kVA) demand for the machine.

Good electrode tip shape and condition are important factors with respect to consistent weld quality. Thus, for production operations, schedules are normally established to provide for the cleaning and the tip dressing (re-machining) of electrode configurations to their original design.

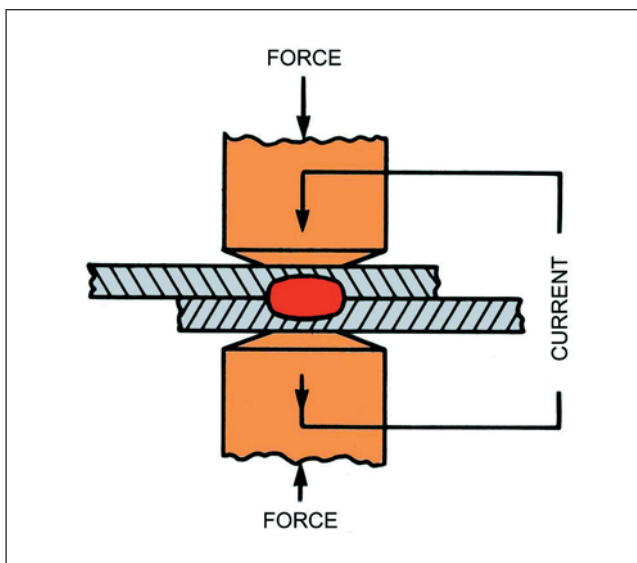
Other important resistance processes include flash welding, upset welding, and high-frequency upset seam welding. Instead of welding lapped surfaces as in the previously described resistance welding processes, the flash, upset, and high-frequency upset seam processes weld together the edges of two workpieces or the edges of a rolled pipe seam. High-amperage alternating current and low voltage are normally used.

Resistance Spot Welding

Resistance spot welding (RSW) involves the application of the welding current through electrodes that concentrate the current and pressure in the area of the weld. A nugget of weld metal is produced at the location where the electrodes are positioned. Figure 1.17 illustrates this concept.

The electrodes used in spot welding not only conduct the welding current to the workpiece but also transmit a compressive force and dissipate heat from the weld zone because the electrodes are internally water cooled. Typically made of copper alloy, they have a straight shank and a conical or domed tip. It takes less than one second to make a single weld with industrial-duty equipment. For example, joining steel sheets that are 1/16 in. (1.6 mm) thick with alternating current only requires 15 cycles (0.25 seconds) of weld time with a weld schedule of approximately 12 000 A current, 800 pounds force, and 4 V voltage.

The basic equipment used in resistance spot welding consists of an electrical circuit, control equipment, and a system to apply force. This process is performed using a variety of equipment designs, ranging from simple utility spot welders to highly sophisticated computer controlled systems. These systems can monitor the welding process in real time and are fast enough to adjust all of the welding parameters during the making



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(A).

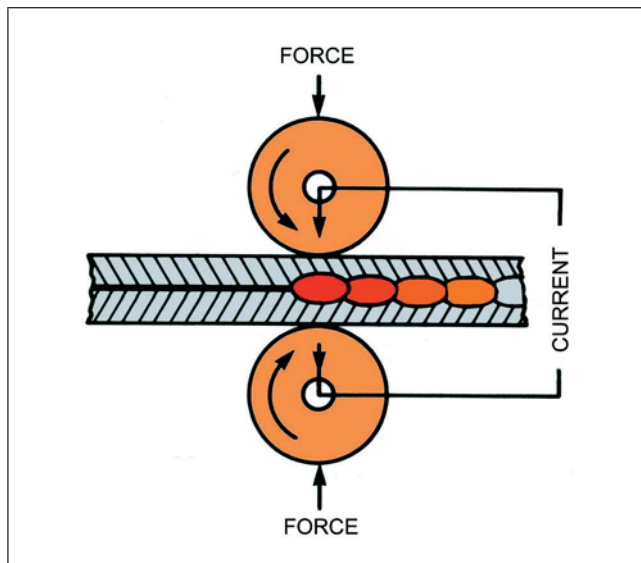
Figure 1.17—Schematic Representation of Resistance Spot Welding

of a single spot weld. This can result in achieving very specific weld sizes and mechanical properties in each weld.

A typical car body contains several thousand spot welds that are made using many coupled weld cells. Each weld cell contains multiple robots that make the spot welds with production rates of up to 90 vehicles completed per hour. Most of the automotive companies use mid-frequency power supplies. Sheet metal shops use less sophisticated systems to join many other thin-gauge products using spot welding. The minimal welding time and operator skill required are the main advantages of this process. The principal disadvantage is the need to have accessibility to both sides of the workpiece as opposed to being able to make welds from one side only.

Resistance Seam Welding

Typically used to produce leak-tight joints in sheet assemblies such as automotive gasoline tanks, resistance seam welding (RSEW) utilizes the fundamentals of resistance welding to produce a continuous seam along the length of the joint. The seam is created with copper wheel-type electrodes that make a continuous weld by generating overlapping spot welds, as shown in Figure 1.18.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(B).

Figure 1.18—Schematic Illustration of Resistance Seam Welding

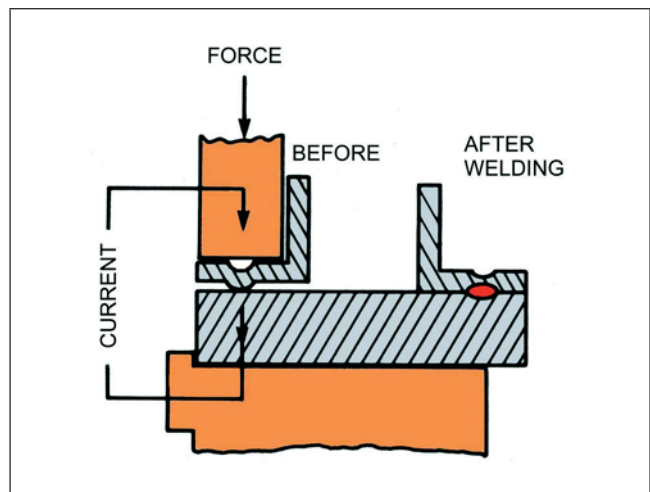
The overlapping of welds causes a shunting effect, (that is, the loss of current density through the intended weld path due to a diversion of some power through a path of less resistance caused by the overlapping welds). To overcome this effect, the current and duty cycles required for resistance seam welding are somewhat higher than those used in resistance spot welding.

Roll spot welding, a variation of resistance seam welding, utilizes current interruptions that are long enough to form a series of individual spot welds that are separated by a predetermined distance, based on the pulsation time and travel speed.

Projection Welding

Projection welding is a resistance welding process that produces welds at predetermined points which are defined by the projections on generally one of the mating parts. These projections are made on the individual parts by stamping embossments or by creating the projections through casting, sintering, forging or machining. The electrodes used in this process are typically flat faced and generally made from harder copper alloys than those used for other resistance welding processes. Figure 1.19 illustrates the projection welding process. Projection welding is used to produce welds in various steels (carbon, stainless and alloy steels) and some nickel alloys.

The most common use of this process is the projection welding of fasteners such as nuts and studs on



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(D).

Figure 1.19—Schematic Representation of Resistance Projection Welding

sheet metal. The process is also used frequently to join sheet metal but can be used in many other application specific configurations.

In this process, one of the two workpieces to be joined is designed to have one or more protrusions or projections. These projections become weld nuggets when the welding current and electrode force are applied. When more than one projection is formed on the part, the height of every projection must be uniform to permit it to be in contact with the second member. This allows each joining member to be heated properly when the current and force are applied. When the thicknesses of the workpieces are unequal, the projection should be located on the thicker piece. This ensures that the heating of both members is balanced, which is conducive to the production of strong welds.

Resistance stud welding is a variation of the resistance projection process. Figure 1.20 illustrates threaded studs with the projections clearly visible. The dimensions of the projections must be controlled precisely, and equal pressure is required on all projections simultaneously. The pressure applied axially by the electrodes must be accurately aligned to produce welds of consistently high quality.

Studs for resistance stud welds are available in carbon steel and some alloy steels. The welding time for a 3/8 in. (9.5 mm) stud is typically 10 cycles of 60 hertz alternating current (0.17 second), which is less than the typical time of 20 cycles (0.33 second) required for drawn arc stud welding. One explanation for this decrease in the time required is due to the extremely high currents used for resistance stud welding. However, the variety of studs is considerably more limited than that indicated for arc and capacitor-discharge stud welding (refer to Figure 1.16).

An advantage offered by resistance projection welding is its short weld time cycle, which leads to high productivity. The ability to produce numerous welds simultaneously with a single set of electrodes is highly desirable compared to processes that are limited to producing one weld at a time. It is important to note, however, that precise control of all projection dimensions is

imperative when multiple welds are made simultaneously. Another advantage offered by this process is that provisions are made to concentrate the heat at the weld locations by the projections themselves, which simplifies the backing side of the circuit.

Flash Welding

Flash welding (FW), illustrated in Figure 1.21, utilizes both a flashing action (i.e., the rapid melting of the metal at the points of contact due to the high current density at the points) and the application of pressure to generate welds at the faying surfaces of butt joints. When the faying surfaces are heated above the melting temperature of the base metals, force is applied immediately to generate the weld. The molten metal is expelled from the interface, the hot metal is upset, and a flash is formed.

In this process, the workpieces are held firmly in copper-alloy jaws or clamps. Typically, one member is held stationary while the other is moved toward it. When contact is made, electric arcing occurs between the abutting edges. The subsequently applied force causes the molten metal to be expelled from the joint, and the metal close to the joint is deformed in a phenomenon known as *upset*. The irregularities and surface impurities are squeezed out into the upset portion, also termed *flash*, yielding a high-quality weld zone. This flash is usually trimmed off for a smooth joint without stress raisers (i.e., changes in the section or surface that cause a concentration of stress, such as at the joint interface around the periphery of a spot weld).

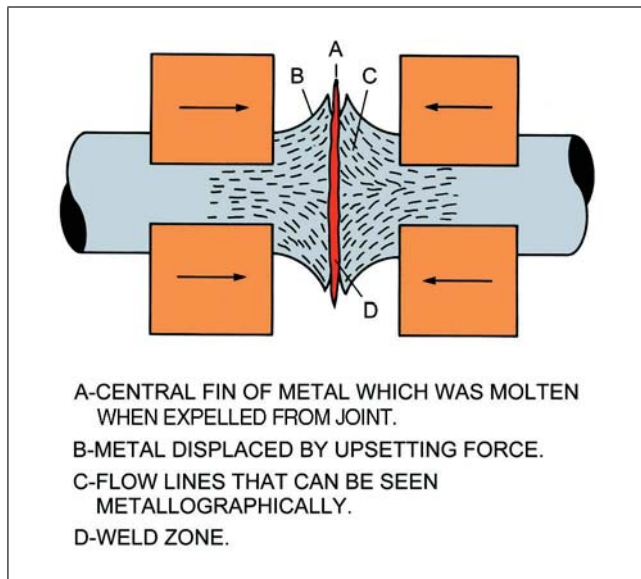
Flash welding, usually an automated process, is widely implemented in the automotive, electrical, and petroleum industries. Applications range from the welding of a variety of material sections such as wires, rods, sheets and shafts. Flash welding, sometimes referred to as flash butt welding, is also extensively used in steel manufacturing, especially in hot strip mill in-process continuous pickling and other coating lines to join coils.

The advantages of flash welding include clean welds (because contaminants are expelled), low operator skill



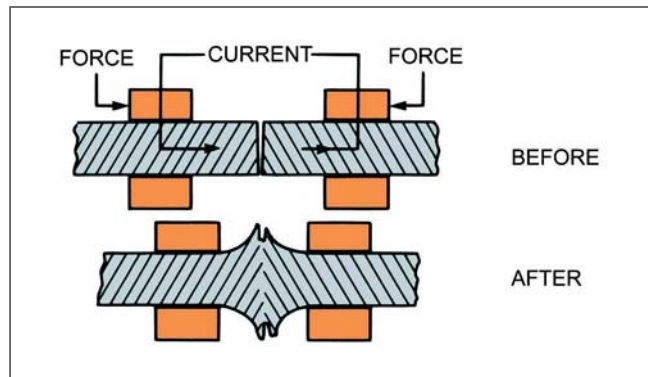
Photograph courtesy of the Ohio Nut & Bolt Company

Figure 1.20—Threaded Fasteners (Studs) Manufactured with Projections for Use in Resistance Stud Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.33.

Figure 1.21—Schematic Illustration of Flash Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.26(E).

Figure 1.22—Schematic Illustration of Upset Welding

required once the process is set up, and off-axial welds can be made such as a mitered corner. The disadvantages are flash can be a fire hazard if not properly controlled, equipment and personnel must be protected from the flash, and more equipment maintenance is required to remove expelled flash material.

Upset Welding

Illustrated in Figure 1.22, upset welding (UW) produces welds by means of the resistance to the flow of the welding current through the area in which the surfaces are in contact and the application of pressure without the formation of an arc. Unlike flash welding, upset welding requires both workpieces to be held together and kept in contact under pressure before current is introduced, and thermal energy develops by resistance heating only. The completed solid-state weld zone is similar to that produced with flash welding. This process is used in wire mill applications and in the fabrication of products made of wire.

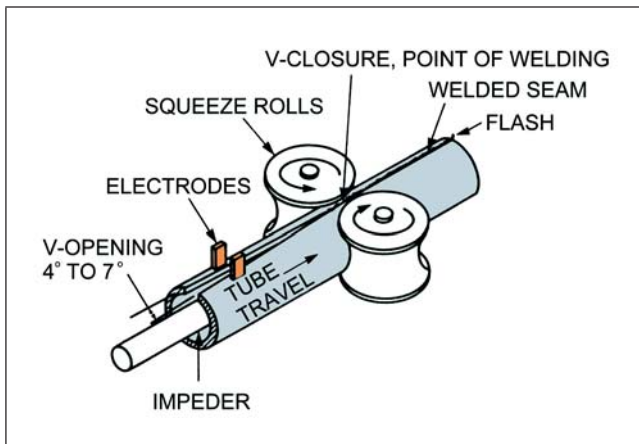
A process variation of upset welding, termed *electric resistance welding*, is used for the creation of longitudinal tubular seams. Although much of the welding current flows around the rolled section, the wheel-type electrodes are close enough to each other to produce sufficient current flow on the edges of the seam mem-

bers for upset welding heat to develop. Squeeze rolls on either side of the tubular section force the edges together. This concept is similar to that used in high-frequency upset welding, except for the manner in which the welding current is introduced, as explained below.

High-Frequency Upset Welding

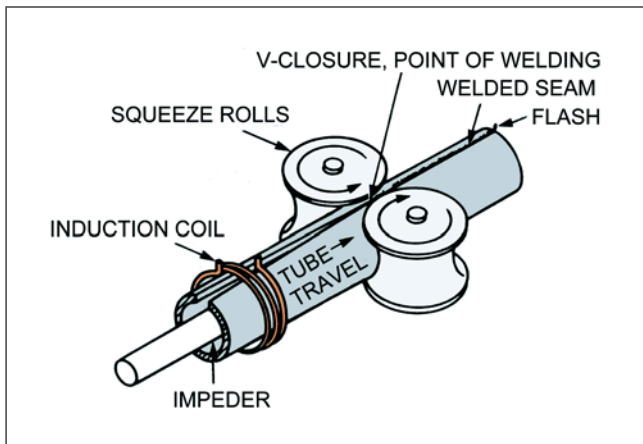
High-frequency upset seam welding (UW-HF) is illustrated in Figure 1.23 and is primarily used in the joining of tubular sections. This process involves the application of high-frequency (hundreds of thousands of hertz) current through the electrodes by either induction or by direct contact with the part, followed by joule heating in the edges of the parts. Two electrical phenomena make this possible, namely the skin effect and the proximity effect.

Initially, a metal strip goes through forming rolls to configure it into a pipe or tube. As the rolled section approaches the welding station, the V-opening of the edges is kept separated at an angle of 4° to 7° to the V-closure (the point of welding). The V-opening makes use of the proximity effect which is the ability of induced currents to concentrate along a close conductor. This opening enables the maximum heating of the edges by the high-frequency current applied to the electrodes. The presence of an internal impeder is essential in concentrating heating to the edges to be joined instead of the rest of the pipe circumference. The impeder achieves concentration of the current flow to achieve maximum edge heating by absorbing the induced currents that would normally travel around the rest of the pipe; therefore it has to be water cooled suffi-



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.29.

Figure 1.23—Schematic Illustration of High-Frequency Upset Seam Welding



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.31.

Figure 1.24—Schematic Illustration of Induction High-Frequency Upset Seam Welding

ciently. The squeeze rolls push the heated edges together to produce the welded seam. The excess metal that has been squeezed out creates flash, which is subsequently trimmed off to create a smooth surface at the welded area.

In contact HF welding, sliding electrodes are preferred over the wheel-type electrodes because only light pressure is needed for this high-frequency, high-current application. When the frequency is increased from 60 hertz (Hz) to 400 kilohertz (kHz), the heating effect is more concentrated but not as deep because eddy currents only penetrate a few thousandths of an inch. This effect is known as the skin effect and because only a small amount of metal is melted during the welding process it results in very high welding speeds and increased productivity. The increase in productivity is driven by increasing resistance heating by a small area of resistivity times the length divided by the area of the conductor. Less electrical power is required when using high-frequency current due to concentrating the heat on the localized skin where needed in the weld joint rather than requiring more energy to heat all of the mass of the parts to be joined. The internal impeder is essential to this welding process. Maintaining its location relative to the weld V-groove and its effective cooling are important process parameters that must be controlled. However, high-frequency current can cause hazards as it broadcasts electrical noise that can affect the performance of sensitive electronic equipment, including pacemakers, that may be in the area.

For noncontact HF welding, an induction coil is used rather than sliding electrodes. Figure 1.24 illustrates the

use of an induction coil for the high-frequency upset welding of butt joints for pipe seams. When using an induction coil, heating is accomplished by inducing high-frequency current using a copper coil that encircles the pipe or tube. The induction coil heating method is preferred when a problem is posed by the electrode contacting the surface of the pipe or tube. However, this heating method is highly dependent on the liftoff effect, which is the dependence of the coil-to-work distance on the induced current. Because of this effect, the concentricity and the distance between the coil to the tube are essential variables in the process which must be controlled.

SOLID-STATE WELDING PROCESSES

The solid-state welding (SSW) processes accomplish joining by the application of pressure at a temperature below the melting point of the base and filler metals. Certain solid-state processes weld at approximately room temperature.

The solid-state processes have the capability to join dissimilar metals that cannot be successfully joined using fusion welding processes because of the differences in melting temperatures and the formation of brittle intermetallic compounds. For example, welding of aluminum to steel is readily accomplished by several solid-state processes because the two materials are not melted and mixed. When iron and aluminum are melted and mixed together, a brittle intermetallic compound

results; however, if iron and aluminum are joined without melting involved, a weld can be made with minimal or controlled brittle intermetallic formation.

The six solid-state processes discussed here are presented in descending order from the highest-temperature process to the lowest-temperature process. These are forge welding (FOW), friction welding (FRW), diffusion welding (DFW), ultrasonic welding (USW), explosion welding (EXW), and cold welding (CW).

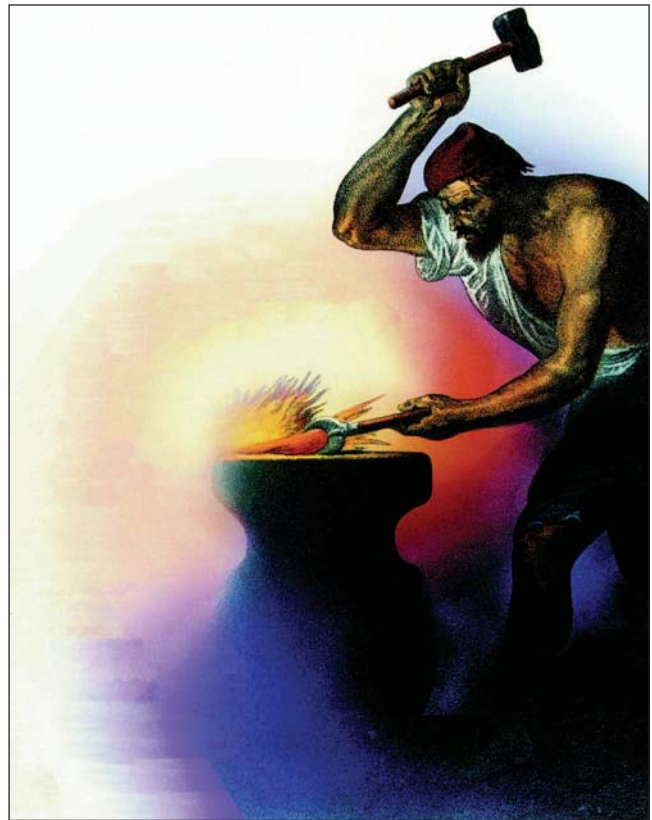
Forge Welding

Forge welding (FOW) accomplishes joining by heating the materials to welding temperature and then applying pressure (hammer blows or steady pressure) to create the weld. Forge welding is one of the oldest known welding processes used by man with use possibly dating back to circa 4000 B.C. Archeologists have found articles such as weapons, anchors, and jewelry that were forged from both ferrous and nonferrous metals. Forge welding may have been accomplished by heating the parts to be joined with the aid of a bellows to a high enough temperature for forging. As illustrated in Figure 1.25, hammer blows were applied to weld and shape the heated portion of the metal.

Forge welding remained the primary welding methods until late in the nineteenth century, when the electric and oxyacetylene processes were developed. At present, some materials are still forge welded using the hammer method, while others are joined using the die and the roll welding (ROW) methods. In the fabrication of laminated coins, for example, three layers of metal are roll welded together before the stamping operation is initiated. Another contemporary application of this process involves welding of low-carbon steels in the production of tubing and clad metals.

Friction Welding

Friction welding (FRW), illustrated sequentially in Figure 1.26, is a solid-state process that accomplishes joining with the heat produced by frictional heat that is generated by the compressive force and the workpieces' rotating or moving in relation to each other which causes the plasticized displacement of material from the faying surfaces. Friction welding machines are therefore designed to convert mechanical energy into heat at the joint to be welded. Normally, one of the two workpieces is circular or nearly circular in cross section. Shielding gas, flux, and filler metal are not required. This process successfully joins a wide range of similar materials as well as a number of dissimilar metals, including aluminum to steel. The oil, defense, aerospace, automotive, electrical, medical, agricultural, and marine industries all employ friction welding.



Source: ESAB, 1990, *Connections*, ESAB Welding and Cutting Products, Hanover, Pennsylvania, p. 2.

Figure 1.25—Ancient Forge Welding

To perform friction welding, a machine rotates one of the workpieces and forces it against the other, which is held stationary. This step is depicted in Figure 1.26(A). As shown in Figure 1.26(B), frictional heat at the joint interface raises the metal to forging temperature. Axial pressure forces the hot metal out of the joint, as can be seen in Figure 1.26(C). Oxides and other surface impurities are removed from the interface and moved into the flashing or expelled material.

Friction welding machines are equipped with a drive head as a means for applying axial force and a yoke or platform for mounting the tooling, which holds the workpiece to be welded in a fixed position as it is being welded. Machines range in size from those capable of welding a 1/2 in. (12.7 mm) diameter steel bar to those that can weld a steel bar 5 in. (127 mm) in diameter. The friction welding cycle is usually automatic. If automatic loading and unloading devices are installed, the machines are completely automatic. As a result, little

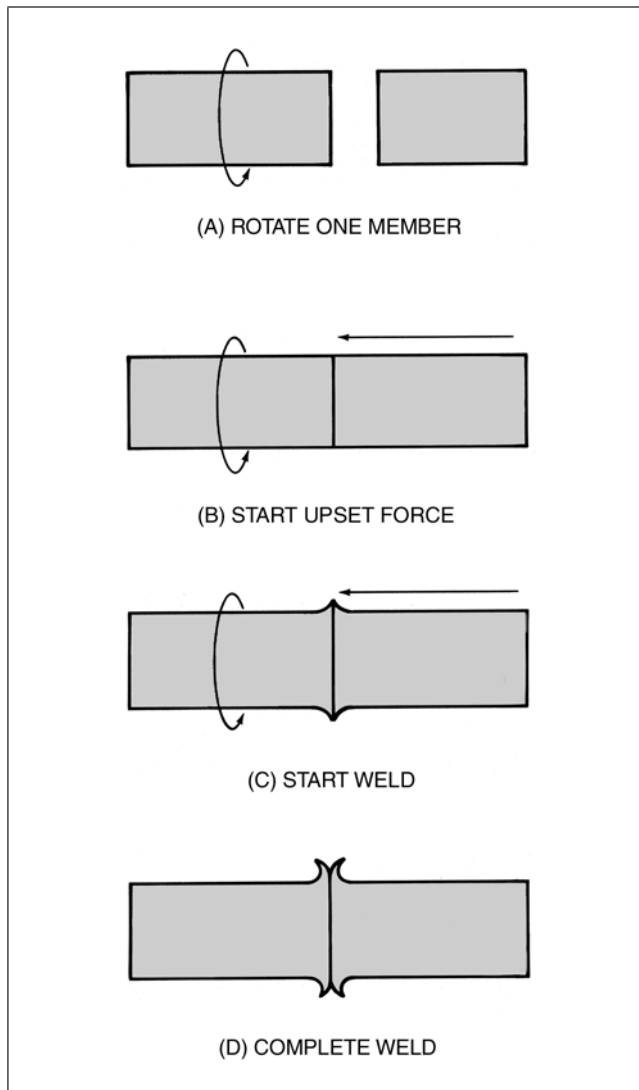


Figure 1.26—Schematic Illustration of Friction Welding

skill in terms of manual dexterity is needed. However, a mechanical aptitude and an understanding of machine operation are required to set up jobs properly and maintain equipment in good operating condition.

Two major process variations of friction welding are commonly employed. In the first, termed *direct drive friction welding*, the moving workpiece is held in a motor-driven collet and rotated at a constant speed while axial force is applied to the stationary workpiece. The stationary part must be held rigidly to resist the axial force and prevent it from rotating. Rotation is

continued until the entire joint is heated sufficiently to ensure that the interface is fully welded upon completion of the welding cycle. Once the correct heating is achieved, the rotation is stopped and an upsetting force is applied to complete the weld. In this case, the welding process variables are rotational speed, axial force, welding time, and upset force. Because energy must be provided at the rate necessary to make the weld, the process requires a relatively high-powered drive motor.

The second variation is known as *inertia friction welding*. In this method, energy is stored in a flywheel, which is accelerated to the required speed by a drive motor. The flywheel is coupled directly to the drive motor by a clutch. The flywheel is also coupled to the collet, which grips the rotating workpiece. A weld is made by applying an axial force through the rotating workpiece while the flywheel decelerates, transforming its kinetic energy to heat at the joint. The weld is completed when the flywheel stops. The welding variables for this process are the flywheel moment of inertia, flywheel rotational speed, axial force, and upset force (if used).

The time required to generate friction welds is measured in seconds. Inertia welds require from less than 0.5 seconds to approximately 15 seconds, exclusive of the time needed to accelerate the flywheel to the designated speed. With either type of machine, the time required to load and unload parts is longer than the actual weld time.

The following are several operational and economic advantages of friction welding:

1. No filler metal is required for all similar and most dissimilar material joints;
2. Flux and shielding gas normally are not required;
3. Solidification defects and porosity are normally not a concern;
4. The process is environmentally clean due to the minimization of sparks, smoke or fumes;
5. Surface cleanliness is not as critical compared to other welding processes;
6. HAZs are narrow;
7. Most engineering materials and dissimilar metal combinations are suited for joining;
8. In most cases, the weld is at least as strong as the weaker of the two materials being joined (high joint efficiency);
9. Operators are not required to have manual skills;
10. The process is easily automated for mass production;
11. Cycle times are short; and
12. Plant requirements, such as space, electrical power and special foundations are minimal.

The following are some limitations of friction welding:

1. In general, one workpiece must have an axis of symmetry and be capable of rotation about that axis;
2. Alignment of the workpieces may be critical to develop uniform frictional heat;
3. Preparation of the interface geometry may be critical in achieving proper heat balance; and
4. Capital equipment and tooling costs are high, but payback periods typically are short for high volume production.

Friction Stir Welding

A more recently developed process variation of friction resistance welding is friction stir welding. This process was initially designed for use with certain aluminum alloys. Figure 1.27 illustrates the basics of the process, in which a cylindrical tool with a diameter of 0.20 in. to 0.24 in. (5 mm to 6 mm) is rotated between the square-groove faying edges. The nonconsumable tool's shoulder develops the frictional heat while the pin in the center mixes the plasticized metals. There are many configurations of tool pin geometries that are selected based on the specific metals to be joined and the resultant weld properties that are required. For aluminum welding, a temperature of 840°F to 900°F (450°C to 482°C) is generated as the

slightly tilted rotating pin travels along the length of the joint, stirring the hot metal, thereby creating the weld. For steel, this temperature can be up to 1700°F (925°C). In aluminum, where tool steels are typically used for the nonconsumable tool material, the tool rotational speed is in the hundreds of RPM with a downforce of about a thousand pounds. A typical aluminum welding speed is 24 in./min (600 mm/min) on an aluminum section thickness of 1/4 in. (6.4 mm).

Aluminum thicknesses ranging from 1/16 in. to 1/2 in. (1.5 mm to 12.7 mm) can be welded by friction stir welding. Though similar to a conventional milling machine equipped with the welding tool rather than a milling machine cutter, friction stir welding equipment produces much more down force than that achievable by standard milling equipment. There have also been enhancements made to the controls and feedback systems on newer friction stir welding machines.

The advantage offered by friction stir welding as compared to friction welding is that the workpieces need not be rotated against each other while being held under pressure. A disadvantage is that the travel speed and cycle time of the weld are longer than for other welding processes. The choice of metals that can be joined by means of friction stir welding is limited, but has been increasing as new tool configurations and tool materials are being developed.

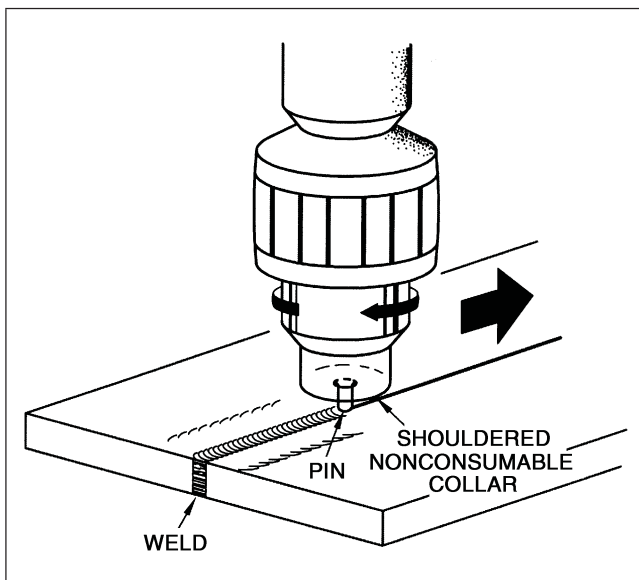
Friction Stud Welding

Friction stud welding is a solid-state welding process in which the stud is rotated at several hundred to several thousand revolutions per minute while being held under hundreds to thousands of pounds force against the surface of the workpiece. At the required temperature, the rotation is quickly stopped, and the pressure on the stud is increased to produce the weld.

An advantage of this type of stud welding is the joining of dissimilar metals because there is no melting of the metals joined during the process. Some combinations form brittle intermetallic compounds when melted and mixed, as is the case with aluminum and steel. However, if the weld is effected by bringing the atoms into close enough proximity to form a bond while in the solid state, these intermetallics are avoided, and satisfactory joint properties can be achieved. On the other hand, the biggest disadvantage of friction stud welding is its lower productivity compared to the other stud welding processes and the process must be mechanized and large fixtures are necessary due to the high downforces and other control requirements.

Diffusion Welding

Diffusion welding (DFW) is a solid-state process that achieves coalescence by applying pressure at high tem-



Courtesy of the Edison Welding Institute

Figure 1.27—Schematic of Friction Stir Welding

peratures with no relative motion or visible deformation of the workpieces and at a temperature that is below the melting temperature of all base metals involved. The process typically takes a long time and is done in a vacuum or in an inert atmosphere. A filler metal may be inserted between the faying surfaces.

Figure 1.28 depicts the stages that result in the joining of two workpieces during diffusion welding. Figure 1.28(A) indicates the asperities (peaks and valleys) of an equiaxed grain structure at the edges of the two workpieces approaching each other with only the peaks touching. Figure 1.28(B) represents the first stage, in which pressure and heat application cause deformation of the grains at the interface of the workpieces, with the boundaries at the interface still defined. Figure 1.28(C) illustrates the second stage, in which diffusion across the boundaries occurs as atoms migrate to new positions and pores from the valleys are eliminated. Figure 1.28(D) depicts the third stage, in which the heat and pressure have continued to the extent that volume diffusion of the atoms has occurred and caused the boundaries to disappear. A new grain formation is evident across the interface, virtually eliminating the pores.

Diffusion welding occurs in the solid state when properly prepared surfaces are in contact under predetermined conditions of time, pressure, and elevated temperature in an inert atmosphere (typically nitrogen) or a vacuum. The applied pressure is set above the level needed to ensure essentially uniform surface contact but below the level that would cause macroscopic (visual) deformation. The temperature is generally well below the melting point and involves long welding times. A filler metal, which is typically positioned before welding as an insert or plating, may be used. In general, the use of filler metal lowers the temperature, pressure, or time required for welding, thereby permitting a more economical welding operation.

The heating required for diffusion welding can be generated in a furnace or retort or by means of electric resistance heating techniques. Pressure is applied by uniaxial fixturing; by dead-weight loading; or by utilizing a press, differential gas pressure, or differential thermal expansion of the workpieces. When joining assemblies with intersecting planar surfaces, high-pressure autoclaves or differential gas pressure techniques can be used. Uniaxial methods of applying pressure are limited to welding parallel planar surfaces roughly per-

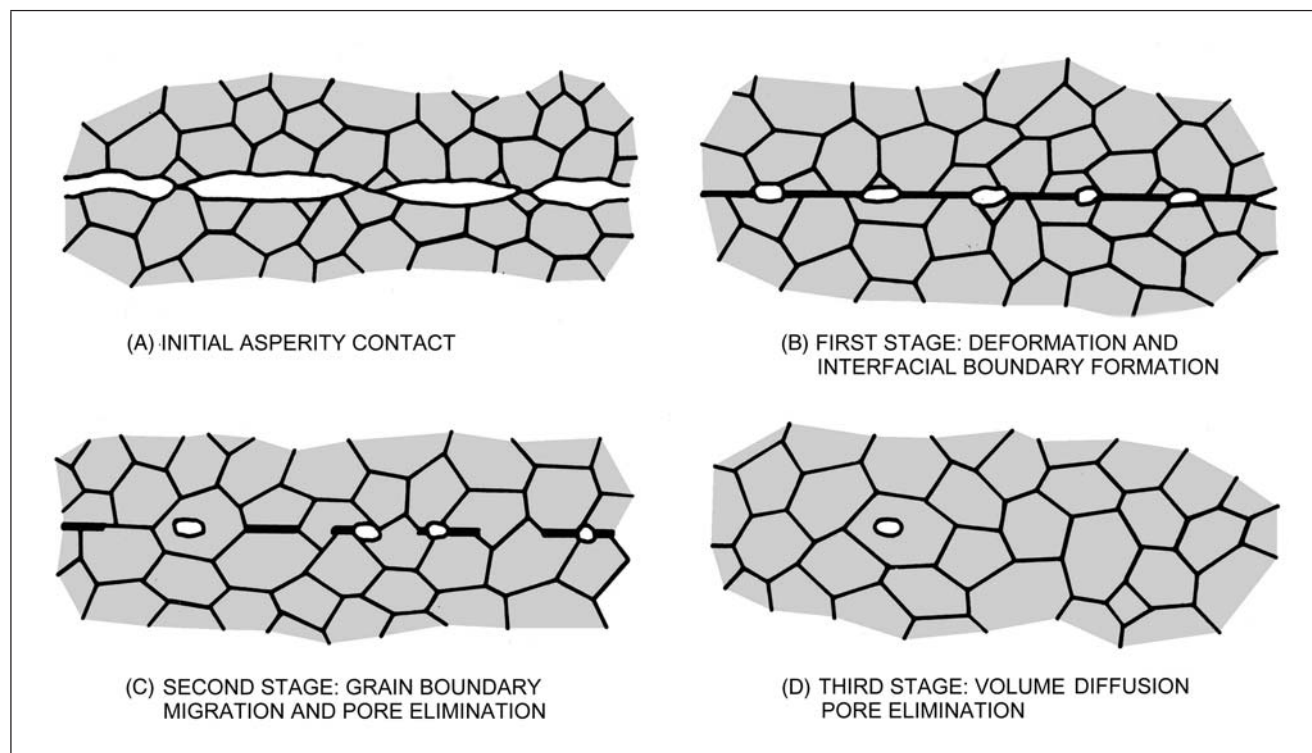


Figure 1.28—Schematic Representation of the Stages of Diffusion Welding

pendicular to the direction of load. These techniques, which are mechanized, require the appropriate fixturing equipment which does not expand with the parts to be joined. These are typically made of ceramics or refractory metals. The encapsulating or “canning” of workpieces to be welded in an evacuated envelope is necessary when differential pressure techniques are applied. The encapsulating of parts is also useful in the implementation of other diffusion welding process variations.

A variety of similar and dissimilar materials can be joined by diffusion welding. Nonetheless, the process has a number of limitations. Equipment costs are high because of the atmosphere or vacuum control as well as the fixturing and temperature monitoring required. Also the time that is required to evacuate the air and backfill with nitrogen can be substantial. This process is economical only when close dimensional tolerances, expensive materials, or special material properties are involved. For this reason, diffusion welding is only used by the aerospace, nuclear, and electronics industries. Although it is sometimes used to fabricate complex, one-of-a-kind devices, it is better suited to moderate production volumes. Diffusion welding is not adaptable to a high production rate, although simultaneous diffusion welding in large batches is possible. Moreover, the costs incurred in the use of consumables are high if precious filler metals or inert gases are used. A high level of operator training is required for most operations. Less skill is required in fully automated operations or once the system has been designed and set up.

Ultrasonic Welding

Ultrasonic welding (USW), used in the semiconductor, microcircuit, electrical, aluminum fabricating, and chemical industries, is a solid-state process that forms a weld by applying localized high-frequency vibratory energy while the workpieces are held together under light pressure. A sound metallurgical bond is produced without significant heat.

The basic equipment required in this process is shown in Figure 1.29. A light clamping force applies pressure through the reed to the sonotrode tip. The transducer is wedge-shaped where it attaches to the reed. It produces the vibration that disrupts surface roughness and impurities prior to welding. The workpieces are placed beneath the sonotrode tip and supported underneath by a fixed component called the anvil. The sonotrode tip and the anvil hold the workpieces together.

Though ultrasonic welding bears some resemblance to resistance welding in that overlapped members are squeezed together at a localized area, ultrasonic welding utilizes no electrical current flow or significant heat across the joint interface. The transducer used in the

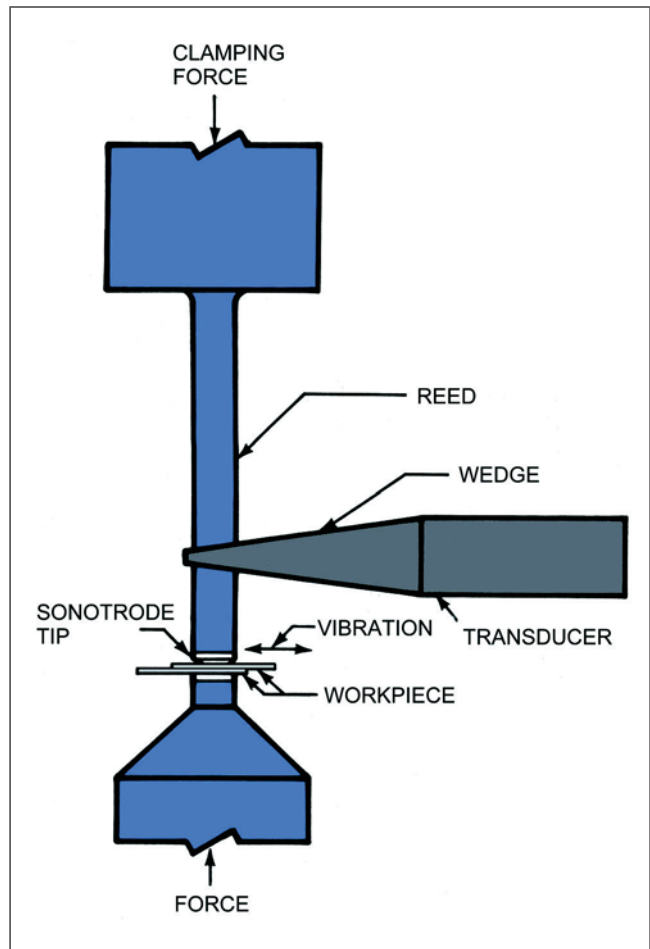


Figure 1.29—Schematic Representation of Ultrasonic Welding

process typically vibrates at 20 kHz or 40kHz with a very small amplitude of 20 microns–30 microns. In USW of metals, the direction of vibration is parallel to the faying surfaces, while for polymers, the direction of vibration is perpendicular to the interface to be joined. The vibratory energy disrupts surface roughness and impurities, interatomic pull occurs, and a weld results. The equipment components must be acoustically tuned to each other or the weld will not take place. It should be noted, however, that the ultrasonic welding process is limited to the size and capability of the transducer.

Process variations have been developed to form welds in spot, ring, line, and seam configurations. Metals such as aluminum and copper, and nonmetals such as thermoplastics are routinely joined by ultrasonic welding. The process has the capacity to weld thin sections to thick sections and to join a variety of dissimilar

materials. For metals, the process is limited to the welding of relatively thin, lapped sections and the joining of wires to sheet or wires to other wires. After the parameters are set, little skill is required to operate the ultrasonic welding process. This process can be used for automatic and robotic applications. High power ultrasonic welding has recently been used in additive manufacturing processes to lay down successive layers of material to build up parts that can contain built-in cavities and embedded sensors.

There are several advantages of the ultrasonic welding process. Many different dissimilar metals can be joined because there is no melting of the materials that occur. Thin sections can be successfully welded to themselves and to thicker metals. The process does not generate much heat which results in less thermal effect on parent metals. There are economic and quality advantages of ultrasonically welding cable over the competing mechanically crimped cables. The process is limited to material thicknesses being under a few millimeters.

Explosion Welding

Explosion welding (EXW) is a solid-state welding process that utilizes a controlled detonation to impact two workpieces at a very high velocity, thereby creating a weld. Explosion welding occurs essentially at ambient temperature though for a few milliseconds, thermal plasma temperatures occur at the interfaces during the explosion itself. As illustrated in Figure 1.30, the explosion accelerates the prime component toward the base component at a speed that causes the formation of a metallic bond between them when they collide. The explosion bends the prime component locally as the detonation quickly progresses. Then, the prime component crosses the standoff distance and impacts the base component. Any localized heating that may be produced by the impact is not significant to the joining process because it lasts for only a short time duration, as welding is primarily accomplished by the plastic flow of the metal pieces across the faying surfaces.

Explosion welding can be used to join metals having sufficient strength and ductility to withstand deformation at the high velocities required and is typically used to join thin metals to dissimilar thicker metals. For example, explosion welding is commonly implemented to join thin-gauge stainless steel or aluminum (the prime component) to thick mild steel (the base component) to create a corrosion-resistant surface on a massive object. In this case, the base component may be supported by a backing if it is not large enough to sustain the impact of explosion welding on its own. Materials combinations that were impossible to weld before, such as uranium to nickel alloys, have been made with this process. Another common use of explosion welding

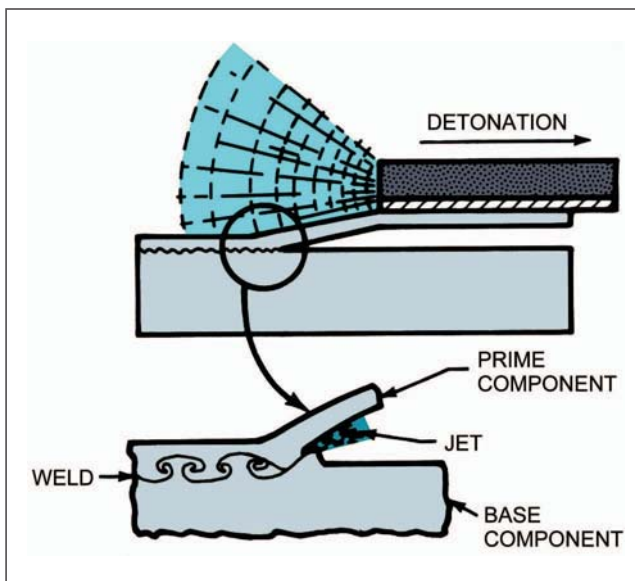


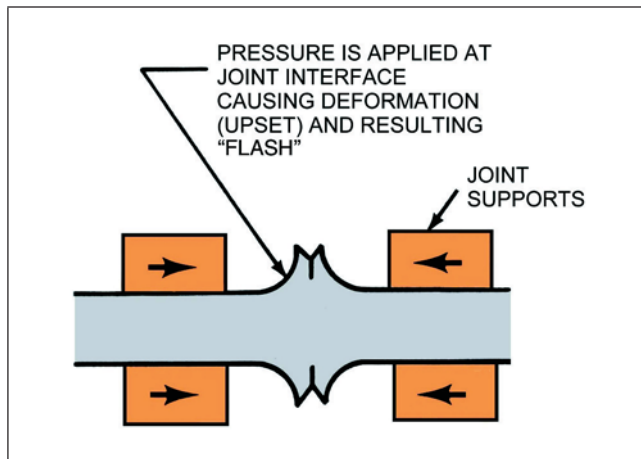
Figure 1.30—Schematic of Explosion Welding

is to create transition pieces between metals that would be otherwise difficult to join, such as steel and aluminum.

Cold Welding

Cold welding (CW) is a solid-state process that uses very high pressure at ambient temperature to effect a weld with substantial plastic deformation of the workpiece. Though this process resembles upset welding, no electrical current flows across the joint and no external applied heat is used; force alone is employed to accomplish joining. As shown in Figure 1.31, the metal must be supported near the joint. A force strong enough to cause localized plastic deformation, which releases thermal energy that further reduces localized yield strength in a very short time and close contact between the faying surfaces is accomplished. Barriers to joining during cold welding are: high yield strength materials, presence of organics and impurities, and most importantly, surface oxides on the faying surfaces before welding. The subsequent upset forces out surface roughness and impurities and promotes interatomic diffusion and formation of a bond.

Not all metals can be joined using the cold welding process. Successful cold welding requires that at least one of the metals being joined be highly ductile with low yield strength and exhibit minimal work hardening, such as metals having a face center cubic structure. Metals that work-harden quickly when deformed start cracking before joining is completed. Metals that have a



Source: Adapted from Kielhorn, W. H., 1978, *Welding Guidelines with Aircraft Supplement*, Englewood, Colorado: Jepperson Sanderson, Figure 2.2.

Figure 1.31—Schematic of Cold Welding

face-centered cubic arrangement of atoms and do not work harden quickly include austenitic stainless steels, aluminum and copper as well as gold, silver, and platinum. Thus, cold welding is used in the manufacture of wire made of these metals. Essential to the process is proper surface preparation before welding, including removal of all oxides, organic contaminants and excessive roughness.

Oxyfuel Gas Welding

Oxyfuel gas welding (OFW) encompasses a group of processes that utilize the heat produced by a combustible gas flame to melt the filler metal, if used, and the base metal, thereby creating a weld. The combustible fuel gas is mixed with oxygen and ignited. The temperature at which it burns is a function of the amount of oxygen present in the gas mixture. If fuel gas with no oxygen added were ignited, aided only by the 20% oxygen contained in ambient atmosphere, the flame temperature would be too low for welding. If the gas were mixed with nearly 100% oxygen, flames would reach temperatures exceeding 5500°F (3038°C). Filler metal and the application of pressure may or may not be used. Oxyfuel gas welding is used mainly in circumstances in which other more modern processes are not available or field applications in remote areas where industrial electrical power is not available. For this application, a nickel or nickel iron based filler rod is used with the oxyfuel gas flame to produce repaired areas that are very similar in properties to the casting itself. If a color difference in the repaired area is accept-

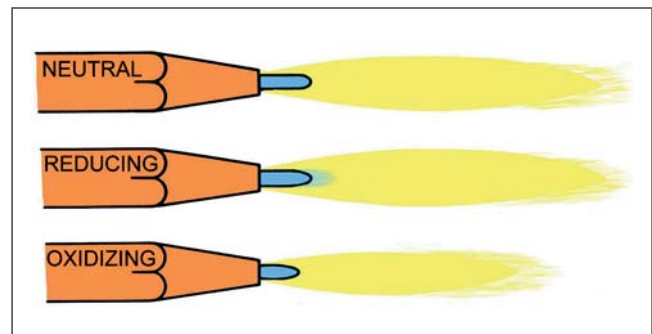
able, an alternate procedure may be used. This involves the use of a brass filler rod to produce a braze weld, which accomplishes the repair without melting any of the cast iron.

The most commonly used fuel gas is acetylene. Compared with other fuel gases, acetylene can produce the hottest and most concentrated flame which can be adjusted from a neutral to a reducing or oxidizing flame. The oxyacetylene flame also produces carbon dioxide, which serves as a shielding gas. Other fuel gases such as stabilized methyl-acetylene-propadiene (MPS) and hydrogen are sometimes used to weld metals with low melting temperatures.

Figure 1.32 demonstrates three types of flames that can be produced with oxyacetylene mixtures. In the illustration at the top, the flame is neutral, containing approximately equal volumes of oxygen and acetylene. The inner cone and outer envelope are the only parts of the flame. The flame is considered neutral because it neither significantly adds to nor subtracts any chemical elements from the weld pool.

It can be noted that the flame illustrated in the middle, known as a *reducing flame*, has a secondary feather extending from the inner cone. This secondary feather is caused by excess acetylene in the flame mixture, which alters the chemical composition of the weld pool by reducing iron oxide (reducing effect) and adding carbon (carburizing effect).

In the bottom flame, oxygen is predominant in the gas mixture and has an oxidizing effect on the weld pool. Referred to as an *oxidizing flame*, this flame has a harmful effect on the properties of ferrous alloys. Like the neutral flame, the oxidizing flame has just two parts. However, it is usually shorter than the neutral or reducing flame and has a sharper point than the neutral flame.



Source: Adapted from Linnert, G. E., 1994, *Welding Metallurgy*, 4th ed., Miami: American Welding Society, Figure 6.58.

Figure 1.32—Types of Oxyacetylene Flames

The rate of heating parts to welding temperature is slower in oxyfuel gas welding than in any other process that uses heat to bring the base metal to the melting temperature. This slow rate of heat input results in increased weld production time, increased energy consumption, and wider HAZ with the attendant coarse-grain structure and poor mechanical properties, especially in high-strength ferrous alloys. When welding metals with excellent heat conduction, such as copper-based alloys, preheat is required to lower the temperature gradient sufficiently to enable the oxyfuel flame to form the weld.

A variation of oxyfuel gas welding known as *pressure gas welding* (PGW) uses the flames to bring the abutting edges to the melting temperature and then applies pressure to force the two workpieces together. This process variation has been mostly replaced by flash welding (FW), which has the capacity to produce welds at a much faster speed.

Oxyfuel gas welding equipment is relatively inexpensive and widely available. As it can also be used for cutting, brazing, soldering, surfacing, and heating applications, it is also extremely versatile. Therefore, the oxyfuel gas process is well suited for small businesses and individual consumers.

OTHER WELDING AND JOINING PROCESSES

Four other welding and joining processes are discussed in this section, which did not fit into the previous groups of welding processes in this chapter. These processes are electron beam welding, laser beam welding, electroslag welding, and adhesive bonding.

Electron beam and laser beam welding are referred to as *high-energy-density processes*. They result in high penetration and high welding speed, which result in low heat input. These processes require automation and have excellent potential for high-speed production. The high-energy-density processes of higher than 10^7 W/cm² are capable of producing welds in which a plasma-filled keyhole full of vaporized material that fully penetrates the metal thickness is surrounded by molten metal. This type of weld, termed a *keyhole weld*, is illustrated in Figure 1.33. As the keyhole reaches the bottom surface, either the welding power beam source or the joint is moved at a speed that allows the molten metal surrounding the plasma expanding in the key hole to flow around to the rear, coalesce, and solidify, forming the weld (see above). These processes are similar to plasma arc welding in that the keyhole is produced with high energy density by means of a constricted arc plasma, but penetration is accomplished by the recoil of a thermal plasma, not high velocity electrical plasma as in PAW.

The most common joint design used in the high-power-density processes is a precisely fitted square-groove butt joint for an autogenous weld. These processes may also use consumables to aid in the joining or to overcome the underfill condition that is typically left on weld beads due to the material that is vaporized during welding. Filler metal can be either shim stock or wire. Shim stock is placed between abutting edges, whereas wire is fed into the joint.

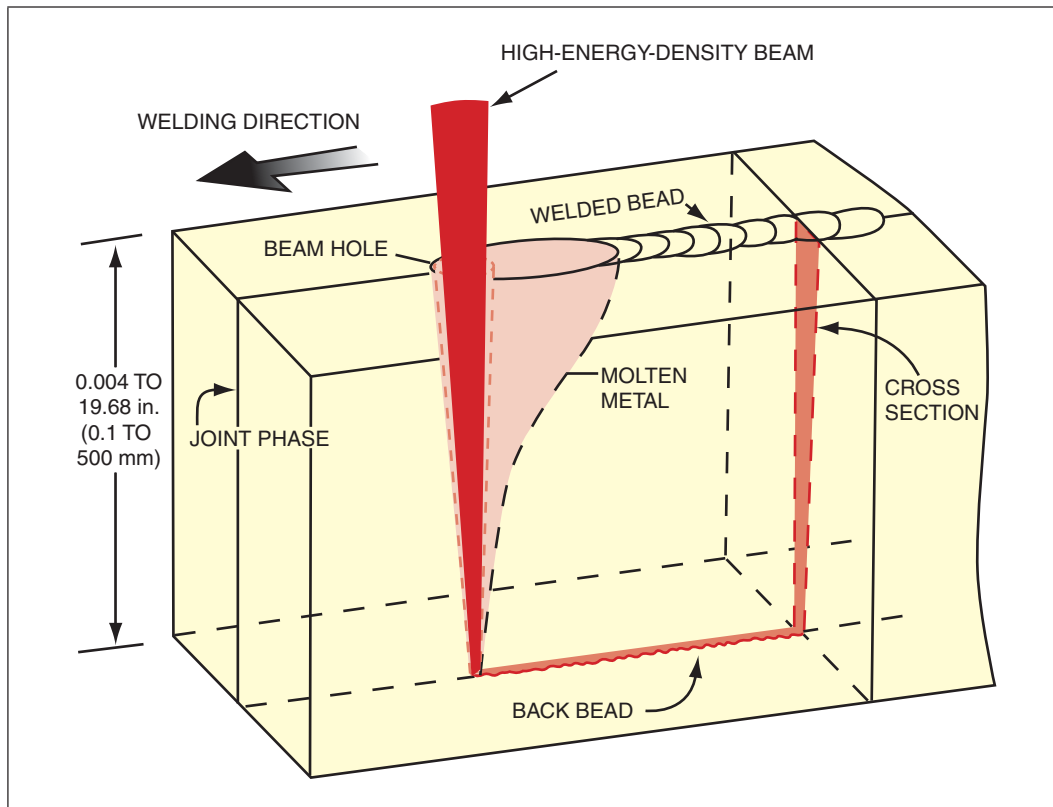
The HAZ in keyhole welding with these processes are normally very narrow and accompanied by rapid cooling rates. Therefore, if slower cooling rates are desired, the joint area to be welded must be preheated.

Electron Beam Welding

Used for high-precision and high-production applications involving most metals, electron beam welding (EBW) accomplishes joining by means of a concentrated stream of high-velocity electrons that is formed into a beam to provide a source of intense local heating. The basic equipment required for most electron beam welding includes a vacuum chamber, controls, an electron beam gun, a three-phase power supply, an optical viewing system or tracking device, and work-handling equipment. The operation of this equipment is almost always automatic.

Electron beam welding is illustrated schematically in Figure 1.34. Electrons are accelerated from the electrically excited, negatively charged cathode at about 200 000 V accelerating voltage. The grid (bias cup) partially shapes the electron beam. The speed of the electrons is greatly accelerated to 30% to 70% of the speed of light and the beam is shaped by the positively charged anode. The beam tends to widen because it is made of similarly charged particles, then passes through the magnetic focusing coil, which focuses it on the weld site. The beam subsequently passes through the magnetic deflection coil, which has deflection capabilities, if these are desired for the application.

The electron beam can be focused in a minute spot 3/64 in. (1 mm) in diameter. As the metal is bombarded by the electrons, the rapid heating produces a vapor hole surrounded by the molten metal that forms the weld. The molten metal flows to the rear of the vaporized hole and coalesces as the workpiece or beam is moved along the joint. The vacuum keeps the electron beam from becoming divergent by colliding with air molecules, and also provides very effective shielding of the workpiece from the atmosphere. Even a moderate vacuum provides better protection from oxidation than inert gas shielding from a nozzle. Precise control of travel along the joint is required for full weld penetration. Moreover, because the electron beam is so small, edge preparation and fitup must be precise. Sufficient



Source: Adapted from Powers, D. E., and G. R. LaFlamme, 1988, EBW vs. LBW—A Comparative Look at the Cost and Performance Traits of Both Processes, *Welding Journal* 67(3): 25–31, Figure 1.

Figure 1.33—Schematic Representation of a Keyhole Weld

shrinkage to cause weld buildup on the surface may occur in thick sections, even without filler metal.

The three process variations of electron beam welding—high vacuum, medium vacuum, and nonvacuum welding—are based on the degree of vacuum used. As shown in Figure 1.34, the high vacuum electron beam welding (EBW-HV) variation, which often is referred to as *hard-vacuum-electron beam welding*, typically utilizes a pressure of 1×10^{-3} torr (1.3×10^{-2} pascal [Pa]). The medium-vacuum variation (EBW-MV) typically employs a vacuum of 2×10^{-1} torr (26.7 Pa). The non-vacuum variation (EBW-NV), often referred to as *atmospheric electron beam welding*, obviously uses no vacuum at all, which is 760 torr (1×10^5 Pa).

Figure 1.35 illustrates the different levels of penetration produced by these process variations. It can be observed that the high vacuum process provides the greatest penetration. With the medium vacuum process, the weld profile is wider and not as deep. The weld pro-

file becomes even wider and shallower with the nonvacuum process.

Several other variables affect joint penetration in high vacuum electron beam welding. These include travel speed, beam power, beam focal point, and beam focus or shape. For example, when welding thin sections, the intensity of the beam can be lowered by changing the shape of the beam into a straight line, a circle, or another configuration.

A major advantage of high vacuum electron beam welding is that it produces deep, narrow welds with low heat input and comparatively narrow HAZs even in materials with high thermal conductivity, such as copper and aluminum. The high vacuum process produces the greatest penetration, with a weld depth-to-width ratio of about 25:1. The narrow HAZ produced is illustrated in Figure 1.36. In addition, very high travel speeds are possible on thin sections. If the speed is too fast, however, joint penetration may be less than 100%,

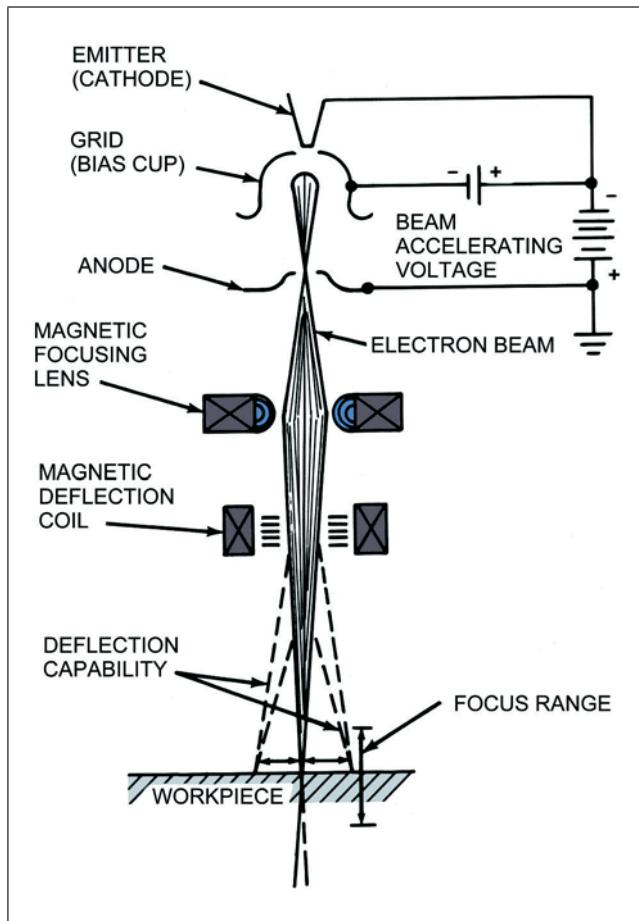


Figure 1.34—Schematic Representation of Electron Beam Welding

and porosity may occur near the weld depth termination. If the travel speed is too slow, the molten metal around the keyhole fails to coalesce causing it to collapse into the keyhole, and no joining takes place. It is also important to note that when welding thick sections of some alloys, magnetic fields cause the beam to curve away from the joint. In this case, the weld will not fully penetrate, and the lower portion of the joint will not be welded.

Electron beam welding has its limitations, however. First, the capital costs associated with this process are substantially higher than those incurred with arc welding equipment, though unit cost is competitive when production volume is high. When performing electron beam welding in a moderate vacuum or no vacuum, atmospheric molecules quickly dissipate the beam energy. This phenomenon may make electron beam

welding less desirable than other processes with considerably smaller capital investments.

In addition, in the high vacuum and medium vacuum variations, a significant amount of pump-downtime is incurred while placing the parts in a vacuum chamber, though welding in a medium vacuum involves less pump-downtime than the high vacuum process. As they require a vacuum chamber, the high and medium vacuum processes are limited with respect to the size of parts that can be welded. Production speed can be augmented by increasing the size of the vacuum chambers to permit them to accommodate more workpieces. Another option to increase productivity is the use of chambers in a circular, or carousel, arrangement. After the workpiece is loaded into the carousel, it is sent at timed intervals through the chambers, where the vacuum becomes progressively higher. In the final chamber, the desired vacuum is attained, and the workpiece is welded.

When performing electron beam welding in a vacuum, porosity and spatter can be caused by the evolution of gas as the metal is melted by the beam, a phenomenon known as *outgassing*. When the evolving gas causes the ejection of molten drops of metal that scatter over the work surface, the solidified drops take the form of spatter. It is important to keep the workpiece clean in order to minimize outgassing. In the presence of a vacuum, the gases and impurities present in the material evolve during welding, causing the workpiece and the chamber to become coated with residue.

In nonvacuum electron beam welding, the vacuum is used only to create the electron beam. Therefore, the weldment size is not limited to the size of a vacuum chamber. However, penetration capability is much lower, and shielding gas is required. In addition, as a vacuum chamber fails to provide protection from the X-radiation emitted by the beam, more contamination occurs. Thus, operators must control the process remotely from outside the required radiation enclosure. Personnel must also be protected from the ozone and other noxious gases produced during the nonvacuum process.

Laser Beam Welding

Laser beam welding (LBW) is a fusion welding process that accomplishes fusion by bombarding the base metal with a high power density light beam. Some of the light energy is reflected but the light energy that is absorbed causes the atoms of the metal to vibrate rapidly changing the photon energy into thermal heat energy. The laser beam is generated from a concentrated beam of coherent, monochromatic light in the infrared or ultraviolet frequency portion of the electromagnetic radiation spectrum. Therefore, the beam is invisible in most welding applications.

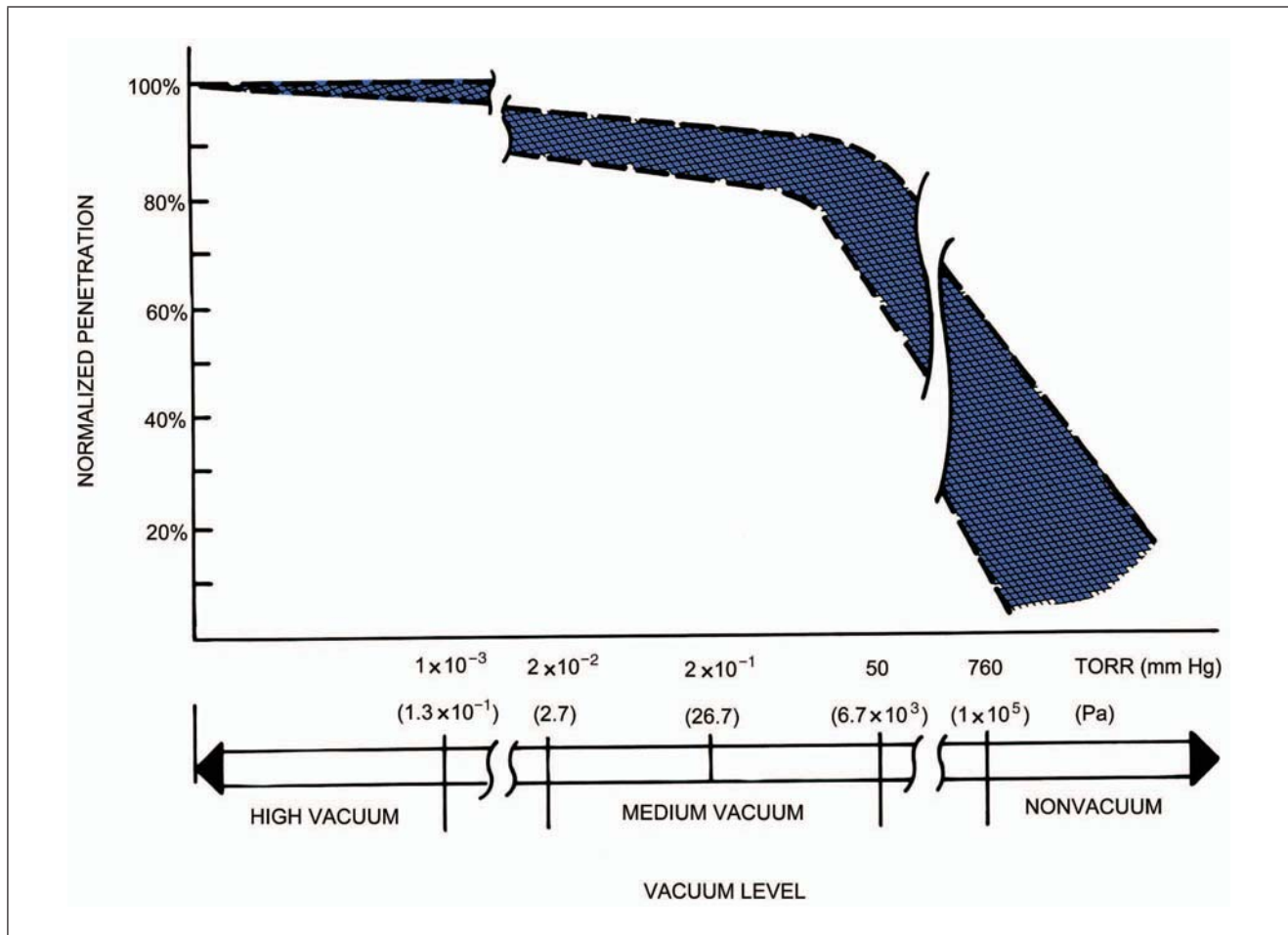


Figure 1.35—Electron Beam Penetration as a Function of Operating Pressure

As illustrated in Figure 1.37, the CO₂ laser beam is directed by mirrors while other laser systems can be fiber optically transmitted and use a flashed solid crystal or a set of disks instead of an excitable gas as the means to create the coherent laser beam. The resulting minimally divergent raw beam is later focused into a small spot by the focusing optics in the laser process head. Consequently, the proper distance between the lens and the focal point of the lens is crucial to obtaining the greatest power density on the base metal.

When comparing power input to power output, laser beam welding is actually rather inefficient. Depending on the type of laser equipment, only 8% to 15% of the electrical power input results in output of photons for a CO₂ laser while the diode laser can reach 40% electri-

cal efficiency. The remainder of the power is consumed in the heating of the laser equipment.

Nevertheless, several lasers have good penetration characteristics. For example, the carbon dioxide gas laser, with rated outputs as high as 25 kilowatts (kW), can produce keyhole welds in steel more than 1 in. (25.4 mm) thick in one pass. A two-pass weld made from both sides also increases penetration capability. Though the yttrium aluminum garnet (YAG) solid-state lasers have power ratings below those recorded by their carbon dioxide counterparts, the YAG lasers are significant in welding, piercing (see the section titled “Laser Cutting” below), and heating applications. There have been many advancements in laser systems such as fiber, diode and disk lasers which are more efficient, have