

Welding Aluminum— Questions and Answers

A Practical Guide for Troubleshooting Aluminum Welding-Related Problems

2nd Edition

by

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Reviewed by the

AWS Product Development Committee

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Preface

The 2nd edition of this book was produced in order to include additional sections which contain material considered important and very appropriate for enhancing the overall content of the publication.

The additional topics that have been added are:

1. The Reduction in Strength of Aluminum Base Material after Welding—and the effect of filler alloy selection on the strength of fillet welds, with tables providing valuable data.
2. Post Weld Processing—how to regain lost strength and return aluminum alloys to their original condition after welding—considerations of both heat treatable and non-heat treatable alloys.
3. Explanations of Aluminum Heat Treatment Terms—such as solid-solution hardening, precipitation hardening, age hardening, natural aging, artificial aging, annealing, stabilizing, and stress-relieving, and their affect on aluminum alloys.
4. The use of Aluminum in Cryogenic Applications—with tables that show how mechanical properties of aluminum alloys increase as the temperature decreases.
5. Exfoliation Corrosion and Intergranular Corrosion in Aluminum—ASTM document designation: B 928/B 928M Standard Specification for High Magnesium Aluminum-Alloy Sheet and Plate for Marine Service and Similar Environments.
6. Modes of Metal Transfer Preferable to Aluminum Welding and Why—with table showing GMAW globular-to-spray transition currents for a selection of aluminum electrode diameters for welding aluminum with pure argon shielding gas.
7. Open Root Joint Welding of Aluminum Pipes—the difference between welding aluminum alloys and steel using the gas tungsten arc welding process for this specialized application.
8. Stud Welding of Aluminum—Drawn Arc Stud Welding of Aluminum and Capacitor Discharge Stud Welding of Aluminum.
9. An Overview of Plasma Arc Cutting of Aluminum—a comparison of plasma arc cutting, laser cutting, and water jet cutting.
10. Brazing and Soldering of Aluminum Alloys—an overview of the many brazing and soldering techniques.
11. Welding Specification for Friction Stir Welding—an overview of the AWS D17.3/ D17.3M:2010, *Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications*.

As with the 1st edition, this book is largely comprised of individual Aluminum Questions and Answers that were originally published over a number of years in the American Welding Society (AWS) *Welding Journal*. The majority of the questions addressed herein originate from inquiries to me, primarily from individuals within the welding fabrication industry.

Also included in this collection of material are some feature articles that I have had published previously in the *Welding Journal*. The welding processes section (Chapter 7) contains information and parameters graciously provided by The Aluminum Association and reproduced from their outstanding publication “Welding Aluminum Theory and Practice—Fourth Edition.” Many of the graphics and charts within this book have been reproduced with permission from ESAB Welding and Cutting Products and were taken from material that is used by ESAB for their aluminum welding technology training programs. This book is not constructed in the format that is typically associated with text books pertaining to similar subjects. That is to say, because of the nature of the material source used for this book, the Aluminum Q&A columns, the individual chapters within this book have been compiled to best highlight and explain that material in a manner that reflects the original question and answer theme. For this reason the book deviates from the more traditional layout of a textbook, where typically you would see all the information on specific topics grouped together more specifically.

The idea for compiling this book originated through inquiries from individuals who followed the Aluminum Q&A column in the *Welding Journal* enthusiastically. They wondered if anyone had ever thought of collecting all the information within the Aluminum Q&A columns together into a practical guide for troubleshooting aluminum welding-related problems. I have tried to present this material in a logical format and have included a fairly comprehensive table of contents and index in an attempt to direct the reader to their appropriate areas of interest. If the information contained in this publication helps individuals to better understand aluminum welding and possibly assists in improving welding quality, then I will be pleased with the overall outcome.

Tony Anderson, CEng, FWeldI, CWEng

Table of Contents

Section	Page
Preface.....	iii
About the Author.....	v
List of Questions.....	xviii
List of Tables	xx
List of Figures.....	xxi
Basic Safety Precautions.....	xxv
 Chapter 1—The Advancement of Aluminum within the Welding Fabrication Industry and its Many Product Design Applications.....	 1
1.1 Introduction	1
1.2 Automotive Industry	1
1.3 Shipbuilding.....	3
1.4 Recreation and Sporting Equipment.....	5
1.5 Transportation and Containers	7
1.6 Defense and Aerospace.....	8
1.7 Conclusion	10
 Chapter 2—What is the History of Aluminum and Aluminum Welding?.....	 11
2.1 Introduction	11
2.2 The Story Behind the Metal.....	12
2.3 Developments in Welding Aluminum.....	13
2.4 The History of Heliarc Welding (Gas Tungsten Arc Welding).....	16
2.5 Gas Welding (Oxyacetylene Welding).....	17
2.6 Stick Electrode Welding (Shielded Metal Arc Welding).....	18
2.7 Conclusion	18
 Chapter 3—Aluminum Alloys and Metallurgy	 19
3.1 The Aluminum Alloy Designation System.....	19
3.1.1 Introduction	19
3.1.2 Wrought Alloy Designation System.....	19
3.1.3 Cast Alloy Designation	20
3.1.4 The Aluminum Temper Designation System.....	20
3.1.5 Aluminum Alloys and Their Characteristics	23
3.1.6 1xxx Series Alloys	23
3.1.7 2xxx Series Alloys	23
3.1.8 3xxx Series Alloys	24
3.1.9 4xxx Series Alloys	24
3.1.10 5xxx Series Alloys	24
3.1.11 6xxx Series Alloys	25

Section	Page
3.1.12 7xxx Series Alloys	25
3.1.13 Conclusion	25
3.2 What is the Affect of Arc Welding on the Heat-Affected Zone (HAZ) of Aluminum Alloys?	26
3.2.1 Introduction	26
3.2.2 The Various Types of Aluminum Alloys	26
3.2.3 The Principal Effects of Alloying Elements in Aluminum	26
3.2.4 Pure Aluminum 1xxx	26
3.2.5 Copper (Cu) 2xxx	26
3.2.6 Manganese (Mn) 3xxx	27
3.2.7 Silicon (Si) 4xxx	27
3.2.8 Magnesium (Mg) 5xxx	27
3.2.9 Magnesium and Silicon (Mg ₂ Si) 6xxx	27
3.2.10 Zinc (Zn) 7xxx	27
3.2.11 How Aluminum Alloys Obtain Their Strength	28
3.2.12 Strain Hardening	28
3.2.13 Heat Treatment	28
3.2.14 The Affect of Arc Welding on the Heat-Affected Zone	28
3.2.15 Nonheat-Treatable Alloys	30
3.2.16 Heat-Treatable Alloys	30
3.2.17 Conclusion	30
3.3 Is There a Filler Alloy that Can be Used to Weld All Aluminum Base Alloys, and How Do I Weld Aluminum Alloys 7075 and 2024?	31
3.3.1 A Filler Alloy for All Aluminum Base Alloys	31
3.3.2 Welding 2024 and 7075	32
3.3.3 Conclusion	33
3.4 What are the Differences Between the Heat-Treatable and Nonheat-Treatable Aluminum Alloys?	33
3.4.1 Understanding the Basic Differences Between Heat-Treatable and Nonheat-Treatable Aluminum Alloys	33
3.4.2 Nonheat-Treatable Aluminum Alloys	33
3.4.3 Heat-Treatable Aluminum Alloys	34
3.4.4 How Does the Type of Material, Heat-Treated or Nonheat-Treated, Affect the Completed Strength of the Weld?	34
3.4.5 Conclusion	35
3.5 What are the Alloying Elements in Aluminum Alloys?	35
3.5.1 The Addition of Alloying Elements to Aluminum	35
3.5.2 The Principal Effects of Alloying Elements in Aluminum	36
3.5.2.1 Copper (Cu) 2xxx	36
3.5.2.2 Manganese (Mn) 3xxx	36
3.5.2.3 Silicon (Si) 4xxx	37
3.5.2.4 Magnesium (Mg) 5xxx	37
3.5.2.5 Magnesium and Silicon (Mg ₂ Si) 6xxx	37
3.5.2.6 Zinc (Zn) 7xxx	37
3.5.2.7 Iron (Fe)	38
3.5.2.8 Chromium (Cr)	38
3.5.2.9 Nickel (Ni)	38
3.5.2.10 Titanium (Ti)	38
3.5.2.11 Zirconium (Zr)	38

Section	Page
3.5.2.12 Lithium (Li).....	38
3.5.2.13 Lead (Pb) and Bismuth (Bi)	38
3.5.3 Conclusion	38
3.6 What are Weldable and Unweldable Aluminum Alloys?	39
3.6.1 The Definition of the Tern “Unweldable”	39
3.6.2 Difficult-to-Weld Alloys	40
3.6.3 Coherence Range	40
3.6.4 The 2xxx-Series Alloys (Al-Cu)	40
3.6.5 The 7xxx-Series Alloys (Al-Zn).....	41
3.6.6 Conclusion	41
3.7 How do I Establish the Strengths of Aluminum Alloys, Base Material, Welds and Filler Alloys?	42
3.7.1 Aluminum Base Alloy Strength	42
3.7.2 Aluminum Filler Metal Strength and As-Welded Aluminum Joint Strength	42
3.7.3 The AWS Filler Metal Classification System for Aluminum	43
3.7.4 Conclusion	44
3.8 What is the Affect of Natural Aging on 6061 Aluminum Base Alloy?	45
3.8.1 The Heat-Treated Condition of the Base Alloy	45
3.8.2 The Affect of Natural Aging After Solution Heat Treatment.....	45
3.8.3 The Affect of Aging on the HAZ	45
3.8.4 Heat-Treatable Filler Alloy	48
3.8.5 Conclusion	48
3.9 What is the Affect of Elevated Service Temperature on 6xxx Series Aluminum Alloys?	48
3.9.1 What is the Reason for this Drop in Hardness and Will the Hardness Drop Further?	49
3.9.2 What is the Phenomenon Behind the Hardness Drop After Heating?	49
3.9.3 Will the Hardness Drop Affect Surface Roughness (Pitting, etc.)?	50
3.9.4 Conclusion	50
3.10 What is Anodized Aluminum?	51
3.10.1 What is Anodizing?	51
3.10.2 How is it Performed?	51
3.10.3 Different Types of Anodizing.....	52
3.10.3.1 Type I—Chromic Acid Anodizing.....	52
3.10.3.2 Type II—Sulfuric Acid Anodizing	53
3.10.3.3 Type III—Hardcoat Anodizing	53
3.10.4 Sealing.....	53
3.10.5 Welding on Anodized Aluminum	53
3.10.6 Anodizing Material After Welding.....	54
3.10.7 Conclusion	54
3.11 Can Stress Corrosion Cracking (SCC) Affect the 5xxx Series Aluminum Alloys?	54
3.11.1 What is Stress Corrosion Cracking (SCC)?	54
3.11.2 The Susceptibility of the 5xxx Series Aluminum-Magnesium Alloys to SCC	55
3.11.3 Is SCC a Problem when Using the 5xxx Series Aluminum Alloys?	56
3.11.4 Conclusion	56

Section	Page
3.12 What are the Primary Considerations When Evaluating the Design Strength of Welded Aluminum Structures?	57
3.12.1 The Reduction in Strength of the Base Material After Welding	57
3.12.2 The Effect of Filler Alloy Selection on the Strength of Fillet Welds	58
3.12.3 Conclusion	59
3.13 What Can be Done to Restore the Lost Strength in Aluminum Weldments After Welding?	60
3.13.1 The Affect of Arc Welding on Material Temper	60
3.13.1.1 Nonheat-Treatable Alloys	60
3.13.1.2 Heat-Treatable Alloys	60
3.13.2 Options Available for Postweld Treatment	62
3.13.2.1 Nonheat-Treatable Alloys	62
3.13.2.2 Heat-Treatable Alloys	62
3.13.2.3 The -T6 Temper	62
3.13.2.4 The -T4 Temper	63
3.13.3 Conclusion	64
3.14 What are the Types of Heat Treatment Used on Aluminum Alloys and How Do They Influence Manufacturing Procedures?	64
3.14.1 Solid-Solution Hardening	64
3.14.2 Precipitation Hardening	65
3.14.3 Annealing	65
3.14.4 Stabilizing	65
3.14.5 Stress-Relieving	65
3.14.6 Refrigeration	66
3.14.7 The Influence of Heat Treatment on Manufacturing Procedures	67
3.14.7.1 Welding	67
3.14.7.2 Forming and Machining	67
3.14.8 Conclusion	67
3.15 Why are Aluminum Alloys Suitable for Low Temperature Application and Why are There No Impact Toughness Requirements for Aluminum Filler Alloys?	68
3.15.1 Cryogenic Applications	68
3.15.2 Test Data Available for Low Temperature Applications	69
3.15.3 Conclusion	70
3.16 How Can I be Assured that I am Using the Correct 5xxx Series Aluminum Alloy for Marine Applications and Thereby Prevent Sensitization and Intergranular Corrosion?	71
3.16.1 The Problem	71
3.16.2 The Action Taken to Prevent Reoccurrence	72
3.16.3 More About the B 928 Standard	72
3.16.4 Conclusion	73
3.17 Where Can I Find Technical Information and Training on Aluminum Welding?	74
3.17.1 Useful Textbooks	74
3.17.2 Training Programs for Aluminum Welding	75
3.17.3 Conclusion	76
Chapter 4—Aluminum Filler Alloys	77
4.1 Filler Alloy Selection for Aluminum Welding	77

Section	Page
4.1.1 Introduction	77
4.1.2 Ease of Welding	77
4.1.3 Critical Chemistry Ranges	77
4.1.3.1 Aluminum/Silicon Alloys—4xxx Series	78
4.1.3.2 Aluminum/Copper Alloys—2xxx Series.....	78
4.1.3.3 Aluminum/Magnesium Alloys—5xxx Series	78
4.1.3.4 Aluminum/Magnesium/Silicon Alloys—6xxx Series.....	78
4.1.4 Crack Sensitivity	78
4.1.4.1 Coherence Range	79
4.1.4.2 The 2xxx Series Alloys (Al-Cu)	80
4.1.4.3 The 7xxx Series Alloys (Al-Zn).....	80
4.1.5 Groove Weld Tensile Strength	81
4.1.6 Ductility.....	82
4.1.7 Corrosion Resistance	82
4.1.8 Service Temperature	82
4.1.9 Postweld Heat Treatment	82
4.1.10 Conclusion	83
4.2 What Filler Alloy Should be Used to Weld 6061?	84
4.2.1 How to Choose the Best Filler Alloy	84
4.2.2 Making the Choice	85
4.2.3 Conclusion	86
4.3 What are the Advantages of 4047 Filler Alloy over 4043?	86
4.3.1 The Difference Between 4043 and 4047 Filler Alloys.....	86
4.3.2 Conclusion	87
4.4 What is the Correct Filler Alloy for Welding 5083 Base Alloy, and is the Filler Alloy I am Using the Reason Why I am Failing the Guided-Bend Tests?	87
4.4.1 What is the Most Appropriate Filler Alloy?	87
4.4.2 Why Did the Welded Samples Fail the Guided-Bend Test?	88
4.4.3 Reasons Why a Welded Sample May Fail the Guided-Bend Test.....	88
4.4.3.1 Discontinuities in the Welded Joint	88
4.4.3.2 Using an Incorrect Testing Fixture	89
4.4.3.3 Improper Sample Preparation	89
4.4.4 Conclusion	89
4.5 Should I Use 4043 or 5356 Filler Alloy?	89
4.5.1 Choosing Between 4043 and 5356	89
4.5.2 Conclusion	90
4.6 Are the 4xxx Series Aluminum Alloys Heat-Treatable Alloys or Nonheat-Treatable Alloys?	91
4.6.1 Postweld Heat Treatment	91
4.6.2 Conclusion	92
4.7 Which Aluminum Filler Alloys are Suitable for Sustained High-Temperature Service?	92
4.7.1 Introduction	93
4.7.2 Evaluation of Most Appropriate Filler Alloy	93
4.7.2.1 Filler Alloy ER4643	93
4.7.2.2 Filler Alloy ER4043	93
4.7.2.3 Filler Alloy ER4047	93
4.7.2.4 Filler Alloy ER5554	93

Section	Page
4.7.3 Conclusion	94
4.8 Filler Alloy Selection Chart	95
Chapter 5 Welding Discontinuities and Weld Testing	99
5.1 How to Avoid Cracking in Aluminum Alloys	99
5.1.1 Introduction	99
5.1.2 The Primary Cracking Mechanism in Aluminum Welds	99
5.1.2.1 The 5xxx Series Alloys (Al-Mg)	100
5.1.2.2 The 6xxx Series Alloys (Al-Mg-Si)	101
5.1.3 Further Considerations	103
5.1.3.1 Coherence Range	105
5.1.3.2 The 2xxx Series Alloys (Al-Cu)	105
5.1.3.3 The 7xxx Series Alloys (Al-Zn)	105
5.1.3.4 Al-Zn-Mg Alloys	105
5.1.3.5 Al-Zn-Mg-Cu Alloys	106
5.1.4 Be Aware	106
5.1.5 Conclusion	106
5.2 Why am I Experiencing Cracking Problems in 6061 Welds when Using Both the GMAW and GTAW Processes?	107
5.2.1 Crack Sensitivity	107
5.2.2 Cracking in GTAW Welds and Why the Welds May be Cracking	107
5.2.3 Cracking in GMAW Welds and Why the Welds May be Cracking	108
5.2.4 Conclusion	109
5.3 Why is the Tensile Strength Too Low in my 6061 Welds?	109
5.3.1 Why the 6xxx Series Base Alloys Loss Strength After Welding and How this Condition Can be Minimized	109
5.3.2 Conclusion	111
5.4 How Do I Avoid Porosity Problems in Aluminum Welds?	111
5.4.1 How Does Porosity Occur	111
5.4.2 Shielding During the Welding Operation	112
5.4.3 Hydrocarbons	113
5.4.4 Moisture	113
5.4.5 Material Preparation Concerns	114
5.4.6 Cleaning Prior to Welding	115
5.4.7 Conclusion	115
5.5 Why am I Having Problems Passing Guided-Bend Tests with 6061 Base Alloy and 4043 Filler Alloy?	115
5.5.1 What is a Guided-Bend Test and When is it Used?	116
5.5.2 Bend Testing Aluminum is Different than Bend Testing Steel	116
5.5.3 Special Bending Conditions for Aluminum Alloys	116
5.5.4 Conclusion	119
Chapter 6 Equipment, Welding Processes, and Welding Procedures	121
6.1 The Repair of Aluminum Structures	121
6.1.1 Introduction	121
6.1.2 Identification of Alloy Type	121
6.1.3 The Repair of Some High-Performance Aluminum Alloys	122
6.1.4 Base Material Strength Reduction After Repair Welding	123

Section	Page
6.1.5	Cleaning and Material Preparation Prior to Welding 124
6.1.6	Conclusion 124
6.2	Why am I Having Feedability Problems when Gas Metal Arc Welding (GMAW) Aluminum? 125
6.2.1	The Importance of Feedability in GMAW Welding of Aluminum 125
6.2.2	How the System Affects Feedability 125
6.2.3	Feeding Systems 126
6.2.4	Conclusion 127
6.3	What Mode of Metal Transfer is the Most Appropriate when Gas Metal Arc Welding Aluminum? 127
6.3.1	Mode of Metal Transfer 127
6.3.2	Short Circuit Transfer 127
6.3.3	Globular Transfer 128
6.3.4	Spray Transfer 128
6.3.5	Making the Choice 129
6.3.6	Pulsed Spray Transfer 129
6.3.7	Conclusion 130
6.4	Is Open Root Welding of Aluminum Pipe Different to Open Root Welding of Steel Pipe? 132
6.4.1	Open Root Joint Welding of Steel Pipes 132
6.4.2	Open Root Joint Welding of Aluminum Pipes 132
6.4.3	Type of Weld Preparation 134
6.4.4	Reference Material for Welding Aluminum Pipe 134
6.4.5	Conclusion 135
6.5	What Shielding Gas should be Used when Arc Welding Aluminum? 136
6.5.1	The Two Commonly Used Shielding Gases for Arc Welding Aluminum 136
6.5.2	Shielding Gas for Gas Metal Arc Welding 136
6.5.3	Shielding Gas for Gas Tungsten Arc Welding 137
6.5.4	Conclusion 138
6.6	What Should I Know About the Storage and Preparation of Aluminum Base Alloys and Filler Alloys? 138
6.6.1	Correct Storage and Preparation is Important 138
6.6.2	Aluminum Oxide 139
6.6.3	Hydrocarbons 139
6.6.4	Storage of Filler Wire 140
6.6.5	Metalworking Methods and Considerations when Plasma Arc Cutting 140
6.6.6	Smut 141
6.6.7	Conclusion 143
6.7	How Can I Minimize Distortion when Welding Aluminum? 143
6.7.1	Considering the Principal Reasons for Distortion 143
6.7.2	What Methods can we Employ to Reduce Distortion? 144
6.7.2.1	Correct Sizes of Welds 144
6.7.2.2	Joint Design 144
6.7.2.3	Intermittent Welds 144
6.7.2.4	Balance Stresses 144
6.7.2.5	Fewer Weld Beads 145
6.7.2.6	Process Selection 145

Section	Page
6.7.2.7 Equal Distribution of Welding Stresses	145
6.7.2.8 Other Welding Sequences.....	145
6.7.2.9 Use the Shrinkage to your Advantage.....	146
6.7.2.10 Jigs and Fixtures	146
6.7.2.11 Use Extrusions to Reduce the Amount of Welding	146
6.7.3 Conclusion	146
6.8 What is the Friction Stir Welding Process and is it Used for Welding Aluminum?	149
6.8.1 All About the Process.....	149
6.8.2 Some Applications.....	150
6.8.3 Conclusion	151
6.9 Can Aluminum be Welded to Steel with the GMAW or GTAW Processes?	151
6.9.1 Methods Used to Facilitate the Welding of Aluminum to Steel	151
6.9.2 Bimetallic Transition Inserts	151
6.9.3 Coating the Dissimilar Material Prior to Welding.....	152
6.9.4 Conclusion	152
6.10 What are Bimetallic Inserts and How are they Made by Explosion Welding?	152
6.10.1 Joining Aluminum to Other Metals.....	153
6.10.2 Bimetallic Transition Inserts	153
6.10.3 Explosion Welding of Aluminum to Other Materials.....	153
6.10.4 Welding of Bimetallic Transition Inserts	155
6.10.5 Principal Applications for Bimetallic Transition Inserts.....	155
6.10.6 Conclusion	156
6.11 Are the Laser Beam and Electron Beam Welding Processes Used for the Welding of Aluminum Alloys?	156
6.11.1 Some Advantages of High Energy Density Beam Welding	156
6.11.2 Laser Beam Welding (LBW).....	157
6.11.3 Operation.....	157
6.11.4 Types of Lasers.....	158
6.11.4.1 CO ₂ Gas Lasers	158
6.11.4.2 Nd:YAG Solid-State Lasers	158
6.11.4.3 Direct Diode Lasers	160
6.11.4.4 Fiber Lasers	160
6.11.5 Electron Beam Welding (EBW)	160
6.11.6 Conclusion	160
6.12 Can Resistance Spot Welding be Used Effectively on Aluminum Alloys?	161
6.12.1 About the Process.....	161
6.12.2 Advantages.....	162
6.12.3 Disadvantages	163
6.12.4 Differences Between Resistance Spot Welding Aluminum and Steel.....	163
6.12.4.1 Surface Oxide	163
6.12.4.2 Coefficient of Thermal Expansion.....	163
6.12.4.3 Thermal Conductivity.....	164
6.12.4.4 Electrical Conductivity	164
6.12.4.5 Electrode Wear.....	164

Section	Page
6.12.5 Conclusion	164
6.13 What is Stud Welding and Can it be Used Successfully on Aluminum?	165
6.13.1 Process Description.....	165
6.13.2 Drawn Arc Stud Welding of Aluminum.....	166
6.13.3 Capacitor Discharge Stud Welding of Aluminum	166
6.13.4 Stud Welding Aluminum—Process Selection.....	167
6.13.5 Quality of Stud Welds in Aluminum	168
6.13.6 AWS Code for Stud Welding Aluminum	168
6.13.7 Conclusion	169
6.14 How does Plasma Arc Cutting of Aluminum Compare with Laser Cutting and Water Jet Cutting?	169
6.14.1 The Most Appropriate Cutting Process	170
6.14.2 Overview of Plasma Arc Cutting of Aluminum.....	170
6.14.3 Comparing Plasma Arc Cutting with Laser and Water Jet Cutting	171
6.14.4 Combination Cutting	173
6.14.5 Conclusion	173
Chapter 7—The Common Welding Processes	175
7.1 Introduction to the GTAW and GMAW Processes	175
7.2 Gas Tungsten Arc Welding of Aluminum Alloys	175
7.2.1 Introduction	175
7.2.2 GTAW Welding with Alternating Current (AC)	177
7.2.3 GTAW Welding with Direct Current Electrode Negative (DCEN)	178
7.2.4 GTAW Welding with Direct Current Electrode Positive (DCEP)	178
7.2.5 GTAW Alternating Current (AC) Equipment	178
7.2.6 Power Sources	179
7.2.7 Shielding Gas for GTAW Welding	180
7.2.8 Welding Torches	180
7.2.9 Tungsten Electrodes	180
7.2.10 Filler Alloy.....	182
7.2.11 Pipe Welding	183
7.2.12 Welding Procedures	183
7.2.13 Conclusion	186
7.3 Gas Metal Arc Welding of Aluminum Alloys	186
7.3.1 Introduction	186
7.3.2 The GMAW Process	186
7.3.3 Equipment.....	188
7.3.4 Power Sources	188
7.3.5 Pulsed GMAW	189
7.3.6 Electrode Feeder and Gun.....	190
7.3.7 Shielding Gas	192
7.3.8 Electrode Wire	193
7.3.9 Welding Procedure Development.....	193
7.3.10 Conclusion	194
7.4 Brazing and Soldering of Aluminum Alloys	198
7.4.1 Brazing	198
7.4.2 Brazeability	199
7.4.3 Filler Metals.....	200

Section	Page
7.4.4 Fluxes.....	200
7.4.5 Chloride Fluxes	201
7.4.6 Fluoride Fluxes	203
7.4.7 Torch Brazing.....	203
7.4.8 Furnace Brazing.....	203
7.4.9 Induction Brazing	204
7.4.10 Dip Brazing	204
7.4.11 Vacuum Brazing.....	204
7.4.12 Joint Designs	204
7.4.13 Fixtures.....	205
7.4.14 Metal Preparation.....	205
7.4.15 Corrosion Resistance.....	205
7.4.16 Removal of Chloride Fluxes.....	206
7.4.17 Soldering.....	207
7.4.18 Solderability	208
7.4.19 Solders	208
7.4.20 Fluxes.....	208
7.4.21 Soldering with an Iron	210
7.4.22 Torch Soldering	211
7.4.23 Abrasion Soldering.....	211
7.4.24 Ultrasonic Soldering	211
7.4.25 Furnace Soldering.....	212
7.4.26 Dip Soldering.....	212
7.4.27 Resistance Soldering.....	212
7.4.28 Joint Strengths.....	212
7.4.29 Corrosion Resistance.....	213
7.4.30 Conclusion	213
Chapter 8—Codes and Standards for Welding Aluminum	215
8.1 Codes and Standards for Welding Aluminum	215
8.1.1 Introduction.....	215
8.1.2 Sources.....	215
8.1.3 American Welding Society (AWS).....	216
8.1.4 American Society of Mechanical Engineers (ASME)	216
8.1.5 Conclusion	217
8.2 The Structural Welding Code for Aluminum	218
8.2.1 Introduction.....	218
8.2.2 About the D1.2 Code	218
8.2.3 Conclusion	219
8.3 What is the AWS A5.10, Specification for Bare Aluminum and Aluminum-Alloy Welding Electrodes and Rods?.....	220
8.3.1 The A5 Series Specifications	220
8.3.2 All About the Specification	220
8.3.2.1 Part A—General Requirements	220
8.3.2.2 Part B—Tests, Procedures, and Requirements.....	220
8.3.2.3 Part C—Manufacture, Identification, and Packaging	221
8.3.3 Conclusion	222
8.4 Is there a specification available specifically for Friction Stir Welding?	222
8.4.1 Friction Stir Welding Specifications	222

Section	Page
8.4.2 AWS D17.3/D17.3M:2010 Specification for Friction Stir Welding of Aluminum Alloys for Aerospace Applications.....	223
8.4.3 Specification Content.....	223
8.4.4 Conclusion	225
Annex A—References and Sources for Further Information	227
Index	229

Chapter 1

The Advancement of Aluminum within the Welding Fabrication Industry and its Many Product Design Applications

1.1 Introduction

When we consider the advancement of aluminum within the welding fabrication industry, it becomes clear that there is a definite need for a better understanding of how to weld this material.

As aluminum welding fabrication has advanced, there have been many questions to answer associated with the welding of this material.

This introduction is intended to point out just a few of the many applications where aluminum is used in the welding fabrication industry today.

The first commercial applications of aluminum were novelty items such as mirror frames and serving trays. Cooking utensils were also a major early marketed product. In time, aluminum grew in diversity of applications to the extent that virtually every aspect of modern life was directly or indirectly affected by its use.

Today, aluminum's unique characteristics of light weight, high strength, high toughness, extreme temperature capability, versatility of extruding, excellent corrosion resistance, and recycling capabilities make it the obvious choice of material by engineers and designers for a variety of welding fabrication applications.

1.2 Automotive Industry

Perhaps the most dynamic advancement of aluminum welding fabrication today is within the automotive industry. Promoted primarily through environmental issues such as increased fuel efficiency, corrosion resistance, and recycling, we are seeing more and more components manufactured in aluminum appearing within the average automobile.

Recent developments of major structural components fabricated entirely from aluminum such as engine cradles, front and rear suspension frames, drive shafts, and wheels are complementing the more traditional nonstructural components such as heat exchangers, radiators, and air conditioning units (see Figures 1.1, 1.2, and 1.3). Many of these welded structural components are manufactured using 6xxx series base alloys, making use of this material's ability to produce complex extruded shapes and



Figure 1.1—Fabricated Wheel Often Manufactured from the 5xxx Series Aluminum Base Alloys



Figure 1.2—Drive Shaft Coupling Made from 6xxx Series Aluminum Alloys

its weldability with the GMAW (MIG) welding process. Another issue, other than fuel efficiency associated with the use of aluminum within this industry, is safety. Aluminum's basic physical characteristics lend themselves to creating automobiles that not only perform better in a collision, but can actually help to prevent crashes altogether. Aluminum's strength-to-weight ratio allows engineers to construct larger vehicle crash zones for better energy absorption. Aluminum structures can be designed to absorb the same energy as steel at only 55% of the weight (see Figure 1.4). This weight saving relates to less kinetic energy to be absorbed in a collision. Aluminum intensive vehicles provide better handling and braking capability, improving their crash-avoidance ability. A vehicle made of conventional material weighing 3300 lbs traveling at 60 mph



Figure 1.3—Fabricated Aluminum Engine Cradle

requires 213 ft to stop. Given the same drive train, an equally sized aluminum-intensive vehicle would weigh 2000 lbs and could stop in 135 ft. Similar improvements are seen in acceleration abilities, when a little extra speed could make the difference in avoiding a collision. Welding procedures used within this industry will vary, but typically, wherever possible, will make use of robotics. A typical thin wall heat exchanger fabrication is making use of the 4047 filler alloy which contains 11.0% to 13.0% silicon and provides exceptional fluidity which helps to reduce leakage rates and improve productivity. The thicker material structural applications within this industry are often able to make use of filler alloy 5356 for its improved strength and impact properties.

1.3 Shipbuilding

The fast ferries projects have advanced the use of aluminum in shipbuilding through the development of a new concept in marine transportation. With an eye on profits, shipping companies are looking at high-speed aluminum ferries as a means of fast, efficient, low-maintenance transport. The term “fast ferries” applies to hydrofoils,

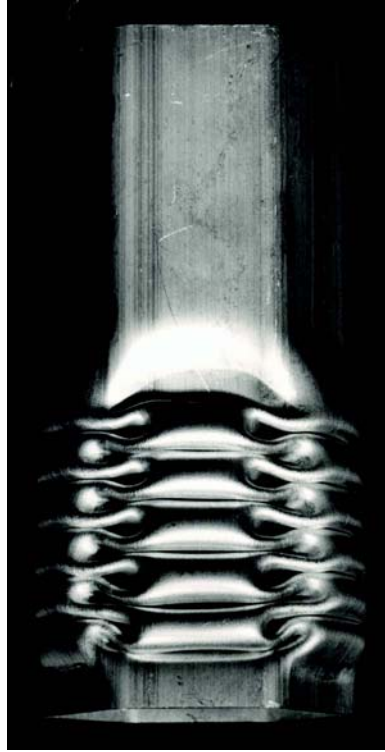


Figure 1.4—During a Car Crash, Aluminum Structures Will Fold Like an Accordion to Absorb Energy and Protect the Vehicle Passengers from Destructive Crash Forces. Pound for Pound, Aluminum Can be Up to Two-and-a-Half Times Stronger than Steel and it Can Absorb Around Twice as Much Energy. Structures Can be Designed to Fold During a Crash in a Predictable Manner.

wave-piercing catamarans and both mono-hulled and multi-hulled vessels built to carry large payloads of passengers and cargo at high speeds. Typically, these vessels are around 100 ft to 130 ft in length and travel at 30 knots to 35 knots [35 mph to 40 mph]. Aluminum-intensive mega-ferries are massive vessels measuring approximately 260 ft in length and carry up to 700 passengers and 150 cars. Quadrimarans are among the newest marine transportation innovations. Measuring 180 ft in length, newer versions are designed to carry 600 passengers. These fast ferries will regularly travel at 60 knots [69 mph] but they could achieve speeds of up to 110 knots [126.5 mph]. The shipbuilding industry has made use of the high-strength magnesium base alloys such as 5083 welded with 5183 filler alloy to obtain the minimum tensile strength requirements as specified in the codes. Often argon/helium shielding gas mixes are used to reduce porosity and obtain broader and deeper penetration for these high-quality welds. Aluminum's unique combination of light-weight, high-strength, and corrosion-resistance make these high-speed marine applications possible. The advantages of aluminum are also being used for military and other types of vessels as well (see Figures 1.5 and 1.6).



Figure 1.5—Large Military Ship Almost Exclusively Manufactured of Aluminum Alloys



Figure 1.6—Coastguard Vessel Made from 5xxx and 6xxx Series Aluminum Alloys

1.4 Recreation and Sporting Equipment

The advancement of high-tech sporting equipment and the increased use of high-strength, heat-treatable aluminum alloys such as the 7xxx series have revolutionized this industry. Many of the latest designs have incorporated these light-weight, high-performance aluminum materials. Bicycle frames, baseball bats, golf clubs, sleds, and snowmobiles are some of the many products within this industry dependent on aluminum alloys today (see Figures 1.7, 1.8, and 1.9). This industry, with its thin wall joining and its complex heat treatment, has promoted the development and use of specialized filler alloys designed to respond to thermal treatment and the development of welding techniques and equipment produced to meet their strength and cosmetic application.



Figure 1.7—High-Performance Bicycle Made from 7xxx Series Aluminum Alloy



Figure 1.8—Snowmobiles are Often Manufactured from Aluminum Alloys



Figure 1.9—Aluminum Baseball Bat

1.5 Transportation and Containers

For similar reasons as the automotive industry, transportation vehicles are adopting more aluminum. Heated rail cars with line heaters and steam lines make use of aluminum base alloy 5454, welded with filler alloy 5554 for their strength and high-temperature characteristics. Cryogenic tanks are manufactured from base alloy 5083, welded with filler alloy 5183 for their high strength at low temperature characteristics. Truck bodies and panels are manufactured from 5052, 5086, 5083, and 6061 and often welded with filler alloy 5356 for its strength characteristics (see Figures 1.10 through 1.13).



Figure 1.10—Dump Trailer Usually Built from 5xxx Series and 6xxx Series Aluminum Alloys

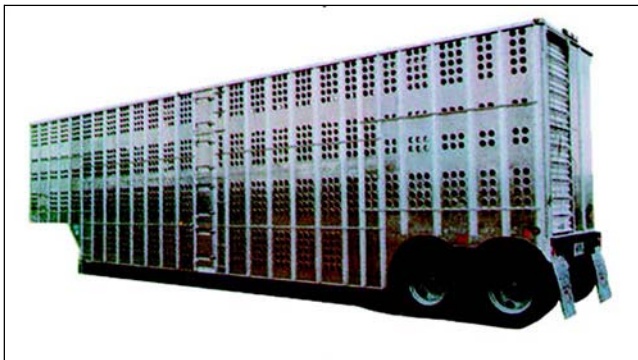


Figure 1.11—Livestock Trailers Make Use of Aluminum's Light Weight and Excellent Corrosion Resistance



Figure 1.12—LNG Tankers Make Use of the Low-Temperature Strength of Aluminum Used for the Manufacturing of These Large Spherical Vessels



Figure 1.13—Aluminum's Light Weight and Corrosion Resistance is Very Suitable for the Fabrication of Many Types of Tanker Trucks

1.6 Defense and Aerospace

These industries use high-strength 5xxx series (Al-Mg) nonheat-treatable base alloys for some applications, but also make use of some of the more specialized heat-treatable aluminum alloys with superior mechanical properties. Aluminum armor plating is used for its impact strength and strength-to-weight ratio (see Figures 1.14 and 1.15). Alloy 5083 and 7039 base materials are welded with 5356 filler, and 2519 base material is welded with 2319 filler. Missiles are constructed of 2019 alloy, welded with 4145 filler and 2219 alloy welded with 2319 filler. Perhaps the most exotic aluminum alloys, with exceptional strength over a wide range of operating temperatures, are used in the aerospace industry (see Figures 1.16 and 1.17). Some of these alloys are 2219, 2014, 2090, 2024, and 7075. These base materials are typically used in specialized high-performance applications and have their own welding characteristics and associated problems, which require special considerations when joining.



Figure 1.14—The Light Weight Allows Aluminum Armored Vehicles Like This to Travel at High Speed



Figure 1.15—The Corrosion Resistance and Light Weight of Aluminum Allows this Military Amphibious Vehicle to Travel at High Speeds on Land and Over Water



Figure 1.16—High-Performance, High-Strength, Heat-Treatable Aluminum Alloys are Used on the Space Shuttle Projects



Figure 1.17—The Space Shuttle Fuel Tank is Fabricated from High-Strength Aluminum Alloys

1.7 Conclusion

The use of aluminum continues to grow within the welding fabrication industry in both size and complexity, and with it the need for resources which can provide industry with the technical support required to understand how best to weld this material.

Chapter 2

What is the History of Aluminum and Aluminum Welding?

2.1 Introduction

To appreciate the history of aluminum welding, it helps if we are familiar with the history of aluminum itself. Today people come into close contact with aluminum on an everyday basis and seldom give the material a second thought. In America alone, nearly 100 billion aluminum beverage cans are used each year. More than 60% of these cans are recycled and made into new aluminum items. Within just one industry sector, the automotive industry, we have seen major advancements in aluminum as a material of preference. The average modern automobile contains more aluminum than ever before. Radiators, engine blocks, transmission housings, wheels, body panels, bumpers, space frames, engine cradles, drive shafts and suspension frames are now commonly made of aluminum and found on many of today's automotive models. As well as our automobiles, homes and office buildings have become more aluminum intensive, incorporating such items as window frames, gutters, electrical wiring, siding, and roofing materials. The homes and offices are also often equipped with furniture made from aluminum alloys.

To appreciate aluminum in today's world, we should remember that it was an aluminum engine that powered the Wright Brothers first flight at Kitty Hawk, North Carolina on December 17, 1903. And, what is probably more relevant, if aluminum had not been available for the development of the aircraft industry, aircraft, as we know them today, would not exist. The extremely high-strength-to-weight ratio of aluminum is the very reason why today's large aircraft can fly with such relatively small engines. The United States is the world's largest producer of aluminum, although it is made in abundance in many other areas of the world. Containers and packaging are aluminum's largest market; transportation (cars, trucks, planes, trains) is second, followed by building and construction. Today, aluminum surrounds us, from cooking utensils that we use in our kitchens to highway signs that guide us down our roads. Aluminum components can be found almost everywhere. As commonplace and important as aluminum is in our everyday lives today, you would suspect that it has been around for a very long time. In actuality, the process of converting aluminum ore into the metal that we know and use everyday as aluminum was discovered relatively recently. Industrial production of aluminum only began in the late 19th century, making this material very much a latecomer among the common metals.

2.2 The Story Behind the Metal

Aluminum is one of 92 metallic elements that have existed since Earth was formed. It makes up about 8% of the earth's crust, exceeded only by oxygen (47%) and silicon (27%). Despite aluminum's abundance, it was not until 2000 years into the Iron Age that it was freed from its mineral state. Over countless millennia, (through physical and chemical action), the ancient aluminum-silicon rocks were ground down to exceedingly fine particles. These particles formed aluminous clays from which primitive pottery was made. In a wide belt around the Earth, hard rain and high temperatures baked and pounded clays and other compounds to form large deposits of aluminum ore. This ore was discovered first at Les Baux, France, where it became known as "bauxite." When the ore was refined, it formed aluminum oxide, also known as "alumina."

For thousands of years, people tried without success to develop something similar to what we now know as metallic aluminum. The primary reason for such a late development of this metal was the difficulty of extracting it from its ore. It combines strongly with oxygen in a compound that, unlike iron, cannot be reduced in a reaction with carbon.

Sometime between 1808 and 1812, Englishman Sir Humphrey Davy was the first to concentrate what he suspected to be a new metal mixed with iron from its naturally occurring ores. Davy named the new element "aluminum," derived from alum, its bisulfate salt, which was known already to the ancient Egyptians for its use in dyeing. Hans Christian Orsted first succeeded in making aluminum on a laboratory scale in Denmark in 1825; Friedrich Wohler did the same in Germany a little later. Finally, in 1854, Frenchman Henri-Etienne Sainte-Clair Deville (who named the ore "bauxite") found a way to produce aluminum through a chemical process. Even though several plants were established to make this new metal, it was so expensive that samples were displayed to the public next to the crown jewels of France at the Paris Exposition of 1855. It took more than 30 additional years before a more economical process of making aluminum was developed.

In 1886 by an amazing coincidence, two men (one in France, and the other in the United States of America) simultaneously discovered the electrolytic process for producing aluminum that is still used today. Charles Martin Hall was an Oberlin (Ohio) College student when he became interested in producing aluminum inexpensively. He continued to use the college laboratory after he graduated in 1885 and discovered his method eight months later. He had ultimately developed a workable electrolytic process that formed molten aluminum when purified alumina was dissolved in a molten salt called cryolite and electrolyzed with direct current. When Hall went to patent his process, he discovered a French patent for essentially the same process, discovered by Paul L. T. Heroult. This process is now known as the Hall-Heroult process. After several unsuccessful attempts by Charles Martin Hall to interest financial backers in promoting the discovery, he obtained the support of Alfred E. Hunt and a few of his friends. Together they formed the Pittsburgh Reduction Company (later to become the Aluminum Company of America, *ALCOA*). Understanding aluminum's potential, Hall founded an industry in the U.S. that contributed to the development of many others, particularly the manufacture of aircraft and automobiles. The industrial production of aluminum began in earnest around 1888 at about the same time in America and in Europe—in the U.S., in Pittsburgh, PA, using Hall's process, and in Switzerland at

Neuhausen using Heroult's process. By 1914, the Hall-Heroult process had brought the cost of aluminum down incredibly. Aluminum, once a precious metal used for fine jewelry, is now becoming an accessible material that can be used to advantage for many applications. Consequently, the production of aluminum multiplied amazingly. In 1918, it had already reached the 180 000 ton level, and it has maintained steady long-term growth ever since. The production and consumption of aluminum grew, on average, through the mid-1970s to more than 8% per year. The total consumption of aluminum in the western world reached 2 million tons in 1952 and 20 million tons in 1989. Aluminum had been recognized as a material of the future.

2.3 Developments in Welding Aluminum

After the initial discovery of a suitable method to produce aluminum as a cost effective material, the next step was to modify and improve upon the basic material.

Pure aluminum has some unique and very important characteristics, its corrosion resistance and electrical conductivity being two of the most important. However, pure aluminum, because of its relatively low strength, was not the most suitable material for structural applications.

It was soon found that by adding relatively small amounts of alloying elements to pure aluminum, major changes could be made to the material's properties. One of the first aluminum alloys to be produced was the aluminum-copper alloy. Around 1910 the phenomenon of precipitation hardening in this family of alloys was discovered. Many of these precipitation-hardening alloys would produce immediate interest within the developing aircraft industry. Following the aluminum-copper alloys, many other alloys were developed; one of these was the 3xxx series alloys which were predominantly used for cookware. Pots and pans were made from these aluminum manganese alloys. The 3xxx series alloys were found to have excellent properties at elevated temperatures and for that reason are still used today for radiators and other heat exchangers. Figure 2.1 shows a Tea Pot Souvenir from the National Aluminium Week held in the U.K. in October 1932.

It was found that by adding such elements as copper (Cu), manganese (Mn), magnesium (Mg), silicon (Si), and zinc (Zn) and combinations of these elements, various physical and mechanical characteristics of pure aluminum could be dramatically changed. Many of these new alloys could match the strength of good quality carbon steel at one third of the weight. The development of many new aluminum alloys, which were suitable for structural application, immediately posed the question of suitable joining methods. It is one thing to have a desirable base material, but without a practical and reliable method of joining such a material, it becomes impractical to use it as a fabrication material.

The development of welding procedures for aluminum alloys was somewhat different than that of carbon steel. Because of the many variations of aluminum base alloys and the different affects each alloying element would have on the weldability of the base materials, it was necessary to develop many different filler alloys to accommodate these variables. For instance, some of the aluminum base alloys were of a particular chemistry, having been designed that way for specific desirable mechanical and physical characteristics that ultimately were proven to not be the most suited to good weldabil-



Figure 2.1—Tea Pot Souvenir from the National Aluminium Week Held in the U.K. in October 1932

ity. These base alloy chemistries were not conducive to the most desirable solidification characteristics, and often rendered the base alloys particularly prone to solidification cracking. The various degrees of solidification crack sensitivity for each of the different alloys needed to be established to provide guidance for the development of suitable welding procedures that would produce consistently crack-free welds. This welding development work was a major project in itself. Much development work was performed by the aluminum base material manufacturers, as it was most certainly to their advantage to show that aluminum could be reliably welded, and also by some of the first aluminum fabricators, who recognized the potential of this new material and were eager to use it within their manufacturing operations. Two of the pioneers in welding development in the U.S. were ALCOA (The Aluminum Corporation of America) and Kaiser Aluminum and Chemical Corporation. Their publication *Welding ALCOA Aluminum* was first published in 1954, and *Welding Kaiser Aluminum* was first published in 1967.

To be competitive in the modern industrial world, a structural metal must be readily weldable. The earliest welding techniques suitable for aluminum included oxyfuel gas welding (see Figure 2.2) and resistance welding. Arc welding of aluminum was mainly restricted to the Shielded Metal Arc Process (SMAW) sometimes referred to as the Manual Metal Arc Process (MMA). This welding process uses a flux-coated welding electrode. It was soon found that this process was not the most suited for welding aluminum. One of the main problems was corrosion caused by flux entrapment, particularly in fillet welds where the flux could be trapped behind the weld and promote corrosion from the back of the weld.

The breakthrough for aluminum as a structural material occurred with the introduction in the 1940s of the inert gas welding processes. Such processes as Gas Metal Arc Welding (GMAW), also referred to as Metal Inert Gas Welding (MIG), and Gas Tung-



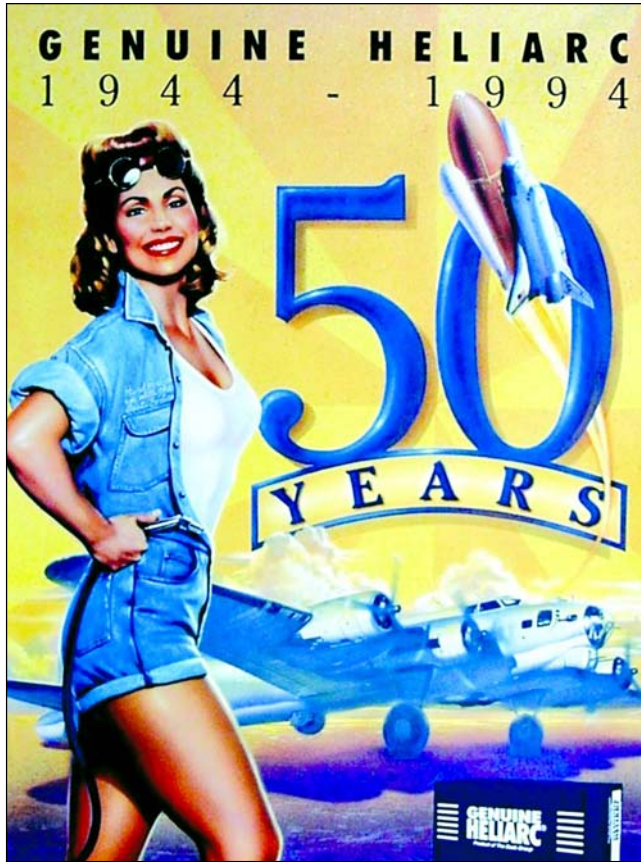
Figure 2.2—U.S. Military Water Bottle Stamped 1918 and Welded with the Oxyfuel Gas Welding Process

sten Arc Welding (GTAW), also referred to as Tungsten Inert Gas Welding (TIG) (see Figure 2.3). With the introduction of a welding process that used an inert gas to protect the molten aluminum during welding, it became possible to make high-quality, high-strength welds at high speeds and in all positions, without corrosive fluxes.

Today, aluminum and its alloys are readily weldable using a variety of techniques and welding processes including newer processes such as Laser Beam Welding (LBW) and Friction Stir Welding (FSW); however, the GTAW/TIG and GMAW/MIG welding processes remain the most popular.

? What is the history behind the welding of aluminum? Is Heliarc welding still a viable option for welding aluminum? Why do we not see as much gas welding or stick electrode welding of aluminum in industry?

A: During my attempt to address these questions, I will also try to clarify some of the terms and definitions used.



Note: Heliarc is a trade name that is used for the GTAW/TIG welding process.

Figure 2.3—1944–1994 Advertisement Celebrating 50 Years of Heliarc

2.4 The History of Heliarc Welding (Gas Tungsten Arc Welding)

Heliarc is an old traditional name, sometimes still used today, for the gas tungsten arc welding (GTAW) process. This same welding process is often referred to as the tungsten inert gas (TIG) welding process (particularly in Europe). The term “Heliarc” refers to the helium that was used as a shielding gas when the process was first used in production because it was the inert gas available at the time.

The GTAW process is quite often a viable option for welding aluminum. It was developed in 1944 and is still extensively used to successfully weld aluminum alloys today. Some of the highest quality welds used in critical applications, such as complete joint penetration pipe welds on cryogenic pressure vessels, are almost exclusively made with this welding process. Alternating current (AC) is used for most applications, but direct current (DC) power is employed for some specialized applications. The GTAW

process was developed earlier than the gas metal arc welding (GMAW) process and for a time was used to weld aluminum of all metal thicknesses and joint types. The GTAW process has since been replaced by the GMAW process for many aluminum welding applications, primarily because of the increased speed of the GMAW process to weld thicker sections. However, GTAW still has an important place in the aluminum welding industry. Gas tungsten arc welding with alternating current and pure argon shielding gas is now most often used to weld thinner gages of aluminum (up to 1/4 in [6.4 mm]) and also for applications where aesthetics are most important.

Alternating current is the most popular method of gas tungsten arc welding aluminum. A balanced wave AC arc provides cleaning action for most applications and divides the arc heat about evenly between electrode and base material. Gas tungsten arc welding power sources for AC welding, which allows for adjustment of the balance between polarities, enables the user to choose either enhanced arc cleaning or greater penetration capabilities. For some more specialized applications, we can find GTAW used in the direct-current electrode-negative (DCEN) mode. This method provides arc concentration of roughly 80% of the heat at the base material and about 20% at the electrode. This results in relatively deep and narrow weld penetration, and very little, if any, significant arc cleaning during the welding operation. Typically used with pure helium shielding gas, this method of welding is capable of welding much greater thicknesses of material (up to 1 in [25 mm]) and is most often used in automatic joint welding applications.

The third mode of GTAW is direct-current electrode-positive (DCEP). With this method, about 20% of the heat is generated at the base plate and 80% at the electrode. It creates excellent cleaning action but very shallow penetration. This is probably the least used method of GTAW.

2.5 Gas Welding (Oxyacetylene Welding)

“Gas welding” is a nonstandard term for the oxyfuel gas welding (OFW) process. This was one of the earliest welding processes used for welding aluminum. Figure 2.2 shows a U.S. Army water canteen welded by the OFW process and dated 1918. This canteen was probably used in the “Great War” (World War I) and was welded around 25 years prior to the development of the inert gas welding processes (GTAW and GMAW). Oxyfuel gas welding is a gas welding process. It achieves coalescence by using the heat from an oxygen-fuel gas flame, and for aluminum, an active flux to remove the oxide and shield the weld pool. Very thick joints have been welded with this process, but the most common applications have been for sheet metal. One of the problems with this welding process is that the flux used is hygroscopic, meaning it absorbs moisture from the surrounding atmosphere. When moist, the flux becomes corrosive to aluminum. Therefore, after welding, the flux must be removed to minimize the chance for corrosion. Because it can be difficult to be certain that all traces of flux have been removed, it was often necessary to finish the operation with an acid dip to neutralize any flux residue. Other disadvantages of using this process for welding aluminum are that mechanical strengths tend to be lower and heat-affected zones (HAZs) wider than with arc welding. Also, it is only practical in the flat and vertical positions, and distortion can tend to be extreme. Most of the problems are attributed to corrosive flux and excessive heat input associated with this process. The oxyfuel gas welding process was widely used for welding aluminum prior to the development of the inert gas welding process; but has limited use today.

2.6 Stick Electrode Welding (Shielded Metal Arc Welding)

This is a nonstandard term for shielded metal arc welding (SMAW).

Prior to the development of the inert gas welding processes (GTAW and GMAW), arc welding of aluminum was mainly restricted to the shielded metal arc welding (SMAW) process, sometimes referred to as the manual metal arc (MMA) process. This welding process uses a flux-coated welding electrode. The electrodes are straight lengths of aluminum rod, coated with flux. The flux acts to dissolve the aluminum oxide on both the base metal and the rod during welding, which is necessary if coalescence is to occur. Some of the flux components vaporize in the arc to form shielding gases that help to stabilize the arc and shield both it and the weld pool from the surrounding atmosphere.

One of the main problems with this welding process is corrosion caused by flux entrapment, particularly in fillet welds where the flux can be trapped behind the weld and promote corrosion from the back of the weld. Other problems are that welds from this process are prone to gross porosity; there are no electrodes available for the high-magnesium-content base metals; and electrodes, once exposed to the air, begin to absorb moisture into the flux, which eventually corrodes the aluminum core and produces excessive porosity problems. It was soon found that this process was not the best suited for welding aluminum. Today's welding codes and standards for aluminum structures do not recognize this welding process.

2.7 Conclusion

Without a doubt, the breakthrough for aluminum as a welded structural material occurred with the introduction in the 1940s of the inert gas welding processes. With the introduction of a welding process that used an inert gas to protect the molten aluminum during welding, it became possible to make high-quality, high-strength welds at high speeds and in all positions without corrosive fluxes.

Chapter 3

Aluminum Alloys and Metallurgy

3.1 The Aluminum Alloy Designation System

In North America, The Aluminum Association Inc. is responsible for the allocation and registration of aluminum alloys. Currently there are close to 500 wrought aluminum alloys and over 250 aluminum alloys in the form of castings and ingots registered with The Aluminum Association. The alloy chemical composition limits for all of these registered alloys are contained in The Aluminum Association's *Teal Book* titled *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloys* and in their *Pink Book* titled *Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot*. These publications can be extremely useful to the welding engineer when developing welding procedures, and when the consideration of chemistry and its association with crack sensitivity is of importance. Aluminum alloys can be categorized into a number of groups based on the particular material's characteristics such as its ability to respond to thermal and mechanical treatment and the primary alloying element added to the aluminum alloy. When we consider the numbering/identification system used for aluminum alloys, the above characteristics are identified. The wrought and cast aluminums have different systems of identification; the wrought having a 4-digit system, and the castings having a 3-digit and 1-decimal place system.

3.1.1 Introduction

With the growth of aluminum within the welding fabrication industry, and its acceptance as an excellent alternative to steel for many applications, there are increasing requirements for those involved with developing aluminum projects to become more familiar with this group of materials. To fully understand aluminum, it is advisable to start by becoming acquainted with the aluminum identification/designation system, the many aluminum alloys available and their characteristics.

3.1.2 Wrought Alloy Designation System

We shall first consider the 4-digit wrought aluminum alloy identification system.

The first digit (**Xxxx**) indicates the principal alloying element, which has been added to the aluminum alloy and is often used to describe the aluminum alloy series, i.e., 1000 series, 2000 series, 3000 series, up to 8000 series (see Table 3.1).

Table 3.1—Wrought Aluminum Alloy Designation System

Alloy Series	Principal Alloying Element
1xxx	99.000% Minimum Aluminum
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc
8xxx	Other Elements

The second single digit (x**X**xx), if different from 0, indicates a modification of the specific alloy, and the third and fourth digits (xx**XX**) are arbitrary numbers given to identify a specific alloy in the series. Example: In alloy 5183, the number 5 indicates that it is of the magnesium alloy series, the 1 indicates that it is the 1st modification to the original alloy 5083, and the 83 identifies it in the 5xxx series.

The only exception to this alloy numbering system is with the 1xxx series aluminum alloys (pure aluminums) in which case, the last 2 digits provide the minimum aluminum percentage above 99%, i.e., Alloy 13**50** (99.**50**% minimum aluminum).

3.1.3 Cast Alloy Designation

The cast alloy designation system is based on a 3 digit-plus decimal designation xxx.x (i.e., 356.0). The first digit (**X**xx.x) indicates the principal alloying element, which has been added to the aluminum alloy (see Table 3.2).

The second and third digits (x**XX**.x) are arbitrary numbers given to identify a specific alloy in the series. The number following the decimal point indicates whether the alloy is a casting (.0) or an ingot (.1 or .2). A capital letter prefix indicates a modification to a specific alloy.

Example: Alloy—A356.0 the capital A (**A**xxx.x) indicates a modification of alloy 356.0. The number 3 (**A3**xx.x) indicates that it is of the silicon plus copper and/or magnesium series. The 56 (**Ax56**.0) identifies the alloy within the 3xx.x series, and the .0 (**Axxx.0**) indicates that it is a final shape casting and not an ingot.

3.1.4 The Aluminum Temper Designation System

If we consider the different series of aluminum alloys, we will see that there are considerable differences in their characteristics and consequent application. The first point to recognize, after understanding the identification system, is that there are two dis-

Table 3.2—Cast Aluminum Alloy Designation System

Alloy Series	Principal Alloying Element
1xx.x	99.000% minimum Aluminum
2xx.x	Copper
3xx.x	Silicon Plus Copper and/or Magnesium
4xx.x	Silicon
5xx.x	Magnesium
6xx.x	Unused Series
7xx.x	Zinc
8xx.x	Tin
9xx.x	Other Elements

tinctly different types of aluminum within the series mentioned above. These are the *Heat-Treatable Aluminum alloys* (those which can gain strength through the addition of heat) and the *Nonheat-Treatable Aluminum alloys*. This distinction is particularly important when considering the affects of arc welding on these two types of materials.

The 1xxx, 3xxx, and 5xxx series wrought aluminum alloys are nonheat-treatable and are strain hardenable only. The 2xxx, 6xxx, and 7xxx series wrought aluminum alloys are heat-treatable and the 4xxx series consist of both heat-treatable and non-heat-treatable alloys. The 2xx.x, 3xx.x, 4xx.x, and 7xx.x series cast alloys are heat-treatable. Strain hardening is not generally applied to castings.

The heat-treatable alloys acquire their optimum mechanical properties through a process of thermal treatment, the most common thermal treatments being Solution Heat Treatment and Aging. Solution Heat Treatment is the process of heating the alloy to an elevated temperature (around 990°F [532°C]) to put the alloying elements or compounds into solution. This is followed by quenching, usually in water, to produce a supersaturated solution at room temperature. Solution heat treatment is usually followed by aging. Aging is the precipitation of a portion of the elements or compounds from a supersaturated solution to yield desirable properties. The aging process is divided into two types: aging at room temperature, which is termed natural aging, and aging at elevated temperatures termed artificial aging. Artificial aging temperatures are typically about 320°F [160°C]. Many heat-treatable aluminum alloys are used for welding fabrication in their solution heat-treated and artificially aged condition.

The nonheat-treatable alloys acquire their optimum mechanical properties through Strain Hardening. Strain hardening is the method of increasing strength through the application of cold working. The Temper Designation System addresses the material conditions called tempers. The Temper Designation System is an extension of the alloy numbering system and consists of a series of letters and numbers which follow

the alloy designation number and are connected by a hyphen. Examples: 6061-**T6**, 6063-**T4**, 5052-**H32**, 5083-**H112**.

The temper designations are listed in detail in Tables 3.3, 3.4, and 3.5.

Further to the basic temper designation, there are two subdivision categories: one addressing the “H” Temper—Strain Hardening, and the other addressing the “T” Temper—Thermally Treated designation.

Table 3.3—The Basic Temper Designations

Letter	Meaning
F	As Fabricated —Applies to products of a forming process in which no special control over thermal or strain hardening conditions is employed.
O	Annealed —Applies to product which has been heated to produce the lowest strength condition to improve ductility and dimensional stability.
H	Strain Hardened —Applies to products which are strengthened through cold-working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The “H” is always followed by two or more digits (see Table 3.4).
W	Solution Heat-Treated —An unstable temper applicable only to alloys which age spontaneously at room temperature after solution heat-treatment.
T	Thermally Treated —To produce stable tempers other than F, O, or H. Applies to product which has been heat-treated, sometimes with supplementary strain-hardening, to produce a stable temper. The “T” is always followed by one or more digits (see Table 3.5).

Table 3.4—Subdivisions of H Temper—Strain Hardened

The first digit after the H indicates a basic operation:	
H1	Strain Hardened Only
H2	Strain Hardened and Partially Annealed
H3	Strain Hardened and Stabilized
H4	Strain Hardened and Lacquered or Painted
The second digit after the H indicates the degree of strain hardening:	
HX2	Quarter Hard
HX4	Half Hard
HX6	Three-Quarters Hard
HX8	Full Hard
HX9	Extra Hard

Table 3.5—Subdivisions of T Temper—Thermally Treated

T1	Naturally aged after cooling from an elevated temperature shaping process, such as extruding
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged
T3	Solution heat-treated, cold worked, and naturally aged
T4	Solution heat-treated and naturally aged
T5	Artificially aged after cooling from an elevated temperature shaping process
T6	Solution heat-treated and artificially aged
T7	Solution heat-treated and stabilized (overaged)
T8	Solution heat-treated, cold worked, and artificially aged
T9	Solution heat-treated, artificially aged, and cold worked
T10	Cold worked after cooling from an elevated temperature shaping process and then artificially aged
Additional digits indicate stress relief. For example:	
TX51 or TXX51	Stress relieved by stretching
TX52 or TXX52	Stress relieved by compressing

3.1.5 Aluminum Alloys and Their Characteristics

If we consider the seven series of wrought aluminum alloys, we will appreciate their differences and understand their applications and characteristics.

3.1.6 1xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 10 ksi to 27 ksi [69 MPa to 186 MPa])

This series is often referred to as the pure aluminum series because these alloys are required to contain a minimum of 99.0% aluminum. They are weldable. However, because of their narrow melting range, they require certain considerations to produce acceptable welding procedures. When considered for fabrication, these alloys are selected primarily for their superior corrosion resistance such as in specialized chemical tanks and piping or for their excellent electrical conductivity as in bus bar applications. These alloys have relatively poor mechanical properties and would seldom be considered for general structural applications. These base alloys are often welded with matching filler material or with 4xxx filler alloys dependent on application and performance requirements.

3.1.7 2xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 27 ksi to 62 ksi [186 MPa to 427 MPa])

These are aluminum/copper alloys (copper additions ranging from 0.7% to 6.8%), and are high-strength, high-performance alloys that are often used for aerospace and

aircraft applications. They have excellent strength over a wide range of temperature. Some of these alloys are considered nonweldable by the arc welding processes because of their susceptibility to hot cracking and stress corrosion cracking; however, others are arc welded very successfully with the correct welding procedures. These base materials are often welded with high-strength 2xxx series filler alloys designed to match their performance, but can sometimes be welded with the 4xxx series fillers containing silicon or silicon and copper, dependent on the application and service requirements.

3.1.8 3xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 16 ksi to 41 ksi [110 MPa to 283 MPa])

These are the aluminum/manganese alloys (manganese additions ranging from 0.05% to 1.8%) and are of moderate strength, have good corrosion resistance, good formability and are suited for use at elevated temperatures. One of their first uses was pots and pans, and they are the major component today for heat exchangers in vehicles and power plants. Their moderate strength, however, often precludes their consideration for structural applications. These base alloys are welded with 1xxx, 4xxx, and 5xxx series filler alloys, dependent on their specific chemistry and particular application and service requirements.

3.1.9 4xxx Series Alloys (Heat-treatable and nonheat-treatable—with ultimate tensile strength of 25 ksi to 55 ksi [172 MPa to 379 MPa])

These are the aluminum/silicon alloys (silicon additions ranging from 0.6% to 21.5%) and contain both heat-treatable and nonheat-treatable alloys. Silicon, when added to aluminum, reduces its melting point and improves its fluidity when molten. These characteristics are desirable for filler materials used for both fusion welding and brazing. Consequently, this series of alloys is predominantly found as filler material. Silicon, independently in aluminum, is nonheat-treatable; however, a number of these silicon alloys have been designed to have additions of magnesium or copper, which provides them with the ability to respond favorably to solution heat treatment. Typically, these heat-treatable filler alloys are used only when a welded component is to be subjected to postweld thermal treatments.

3.1.10 5xxx Series Alloys (Nonheat-treatable—with ultimate tensile strength of 18 ksi to 51 ksi [124 MPa to 352 MPa])

These are the aluminum/magnesium alloys (magnesium additions ranging from 0.2% to 6.2%) and have the highest strength of the nonheat-treatable alloys. In addition, this alloy series is readily weldable, and is used for a wide variety of applications such as shipbuilding, transportation, pressure vessels, bridges, and buildings. The magnesium base alloys are often welded with filler alloys, which are selected after consideration of the magnesium content of the base material, and the application and service conditions of the welded component. Alloys in this series with more than 3.0% magnesium are not recommended for elevated temperature service above 150°F [66°C] because of their potential for sensitization and subsequent susceptibility to stress corrosion cracking. Series 5xxx alloys with less than approximately 2.5% magnesium can be welded successfully with the 5xxx or 4xxx series filler alloys. Because of problems

associated with eutectic melting and associated poor as-welded mechanical properties, it is not recommended to weld material in this alloy series that contain higher amounts of magnesium with the 4xxx series fillers. The base alloy 5052 is generally recognized as the 5xxx series alloy that has the maximum magnesium content that can be successfully welded with a 4xxx series filler alloy. It is recommended that the higher magnesium content base materials only be welded with 5xxx filler alloys, which generally match the base alloy composition.

3.1.11 6xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 18 ksi to 58 ksi [124 MPa to 400 MPa])

These are the aluminum/magnesium–silicon alloys (magnesium and silicon additions of around 1.0%) and are found widely throughout the welding fabrication industry, used predominantly in the form of extrusions, and incorporated in many structural components. The addition of magnesium and silicon to aluminum produces a compound of magnesium-silicide, which provides this material its ability to become solution heat-treated for improved strength. These alloys are naturally solidification crack sensitive, and for this reason, they should not be arc welded autogenously (without filler material). The addition of adequate amounts of filler material during the arc welding process is essential to provide dilution of the base material, thereby preventing the hot cracking problem. They are welded with both 4xxx and 5xxx filler materials, dependent on the application and service requirements.

3.1.12 7xxx Series Alloys (Heat-treatable—with ultimate tensile strength of 32 ksi to 88 ksi [221 MPa to 607 MPa])

These are the aluminum/zinc alloys (zinc additions ranging from 0.8% to 12.0%) and comprise some of the highest strength aluminum alloys. These alloys are often used in high-performance applications such as aircraft, aerospace, and competitive sporting equipment. Like the 2xxx series of alloys, this series incorporates alloys which are considered unsuitable candidates for arc welding, and others, which are often arc welded successfully. The commonly welded alloys in this series, such as 7005, are predominantly welded with the 5xxx series filler alloys.

3.1.13 Conclusion

Today's aluminum alloys, together with their various tempers, comprise a wide and versatile range of manufacturing materials. For optimum product design and successful welding procedure development, it is important to understand the differences between the many alloys available and their various performance and weldability characteristics. When developing arc welding procedures for these different alloys, consideration must be given to the specific alloy being welded to make sure that the correct steps have been taken to ensure the highest quality results. It is often said that arc welding of aluminum is not difficult, "it's just different." I believe that an important part of understanding these differences is to become familiar with the various alloys, their characteristics, and their identification system.

3.2 What is the Affect of Arc Welding on the Heat-Affected Zone (HAZ) of Aluminum Alloys?

3.2.1 Introduction

To appreciate the affect of arc welding on the heat-affected zone of various aluminum alloys, it is necessary to evaluate the various types of aluminum alloys, how these alloys obtain their strength and the potential for changes in strength after welding.

3.2.2 The Various Types of Aluminum Alloys

Considering the seven aluminum alloy series used for wrought alloys, the main alloying elements used for producing each of the alloy series are immediately identifiable. Further examination of each of these elements’ effects on aluminum is possible.

<i>Series</i>	<i>Primary Alloying Element</i>
1xxx	Aluminum—99.00% or Greater
2xxx	Copper
3xxx	Manganese
4xxx	Silicon
5xxx	Magnesium
6xxx	Magnesium and Silicon
7xxx	Zinc

3.2.3 The Principal Effects of Alloying Elements in Aluminum

The principal effects of alloying elements in aluminum are discussed below.

3.2.4 Pure Aluminum 1xxx

Although the 1xxx series are almost pure aluminum, they will respond to strain hardening, especially if they contain appreciable amounts of impurities such as iron and silicon. However, even in the strain-hardened condition, the 1xxx series alloys have very low strength when compared to the other series of aluminum alloys. The most common applications for the 1xxx series alloys are aluminum foil, electrical buss bars, metallizing wire and some chemical tanks and piping systems. These alloys are non-heat-treatable.

3.2.5 Copper (Cu) 2xxx

The aluminum-copper alloys typically contain between 2% to 6% of copper, with small additions of other elements. The copper provides substantial increases in strength and facilitates precipitation hardening. These alloys include some of the highest strength heat-treatable aluminum alloys. The most common applications for the 2xxx series alloys are aerospace, military vehicles, and rocket fins.

3.2.6 Manganese (Mn) 3xxx

The addition of manganese to aluminum increases strength to an extent through solution strengthening. It improves strain hardening and does not significantly reduce ductility or corrosion resistance. These are moderate strength nonheat-treatable materials that retain strength at elevated temperatures. However, for major structural applications, they are rarely used. The most common applications for the 3xxx series alloys are cooking utensils, radiators, air conditioning condensers, evaporators, heat exchangers beverage containers, residential siding, and handling and storage equipment.

3.2.7 Silicon (Si) 4xxx

The addition of silicon to aluminum reduces melting temperature and improves fluidity. Silicon alone in aluminum produces a nonheat-treatable alloy; however, in combination with magnesium, it produces a precipitation hardening heat-treatable alloy. Consequently, there are both heat-treatable and nonheat-treatable alloys within the 4xxx series. The most common application for silicon additions to aluminum is the manufacturing of aluminum castings. The most common applications for the 4xxx series alloys are filler wires for fusion welding and brazing of aluminum.

3.2.8 Magnesium (Mg) 5xxx

The addition of magnesium to aluminum increases mechanical properties through solid solution strengthening. Additionally, it improves their strain hardening ability. These alloys are the highest strength nonheat-treatable aluminum alloys. They are considered optimal for and extensively used for structural applications. The 5xxx series alloys are produced mainly as sheet and plate and only occasionally as extrusions. These alloys strain harden quickly, therefore, they are difficult and expensive to extrude. Some common applications for the 5xxx series alloys are truck and train bodies, buildings, armored vehicles, ship and boat building, chemical tankers, pressure vessels, and cryogenic tanks.

3.2.9 Magnesium and Silicon (Mg₂Si) 6xxx

The addition of magnesium and silicon to aluminum produces the compound magnesium-silicide (Mg₂Si). The formation of this compound provides the 6xxx series their heat-treatability. The 6xxx series alloys extrude both easily and economically. For this reason, they are most often found in an extensive selection of extruded shapes. These alloys form an important complementary system with the 5xxx series alloy. The 5xxx series alloy used in the form of plate and the 6xxx series used in an extruded form are often joined to the plate. Some of the common applications for the 6xxx series alloys are handrails, drive shafts, automotive frame sections, bicycle frames, tubular lawn furniture, scaffolding, stiffeners and braces used on trucks, boats, and many other structural fabrications.

3.2.10 Zinc (Zn) 7xxx

The addition of zinc to aluminum (in conjunction with some other elements, primarily magnesium and/or copper) produces heat-treatable aluminum alloys of the highest

strength. The zinc substantially increases strength and permits precipitation hardening. Some of these alloys can be susceptible to stress corrosion cracking and for this reason are not usually fusion welded. Other alloys within this series are often fusion welded with excellent results. Some of the common applications of the 7xxx series alloys are aerospace, armored vehicles, baseball bats, and bicycle frames.

3.2.11 How Aluminum Alloys Obtain Their Strength

As seen above, aluminum alloys consist of both heat-treatable and nonheat-treatable types. The addition of alloying elements to aluminum is the principal method used to produce a selection of different materials used in a wide assortment of applications. The principle reason for adding the major alloying elements is to facilitate an improvement in the alloys physical and/or mechanical characteristics. Typically, addition of primary alloying elements to aluminum is to provide improvement in strain hardening and/or precipitation hardening characteristics.

3.2.12 Strain Hardening

Strain hardening, used extensively to produce the strain-hardened tempers in the nonheat-treatable aluminum alloys, is an important process that increases the strength of materials that heat treatment cannot strengthen. This process involves a change of shape brought about by the input of mechanical energy. As deformation proceeds, the material becomes stronger but harder and less ductile. For example, the strain hardened temper of H18, full-hard material is obtainable with a cold work equal to about a 75% reduction in area. The H16, H14, and H12 tempers obtained with lesser amounts of cold working represent three-quarter-hard, half-hard, and quarter-hard conditions, respectively.

3.2.13 Heat Treatment

Precipitation hardening of aluminum alloys is accomplished by a solution heat treatment that is followed by aging of the material. Solution heat-treating is achieved by heating a material to a suitable temperature, holding at that temperature for a long enough time to allow constituents to enter into solid solution, then cooling rapidly to hold the constituents in solution. Usually this is followed by precipitation hardening, or what is also termed artificial aging. This is achieved by reheating the alloy to a lower temperature and holding it at this temperature for a prescribed period. The result is to produce a metallurgical structure within the material that provides superior mechanical properties. If, during heat treatment, the material is held at temperature for too long or the temperature used is too high, the material will become over-aged, resulting in a decrease in tensile strength. It is important to recognize that the precipitation hardening process is both time and temperature controlled.

3.2.14 The Affect of Arc Welding on the Heat-Affected Zone

To make a welded joint in an aluminum structure using the arc welding process melting of the base material must occur. During the melting operation, heat transfers through conduction into the base material adjacent to the weld. Typically, the completed weldment is divided into three distinct areas: the weld metal, the heat-affected zone adjacent to the weld, and the base material beyond the HAZ that has been unaf-

affected by the welding operation. Because the HAZ will experience cycles of heating and cooling during the welding operation, arc welding on materials which have been strengthened by strain hardening or precipitation hardening, will change its properties and may be extremely different than that of the original base alloy and the unaffected area of the base material (see Figures 3.1 and 3.2).

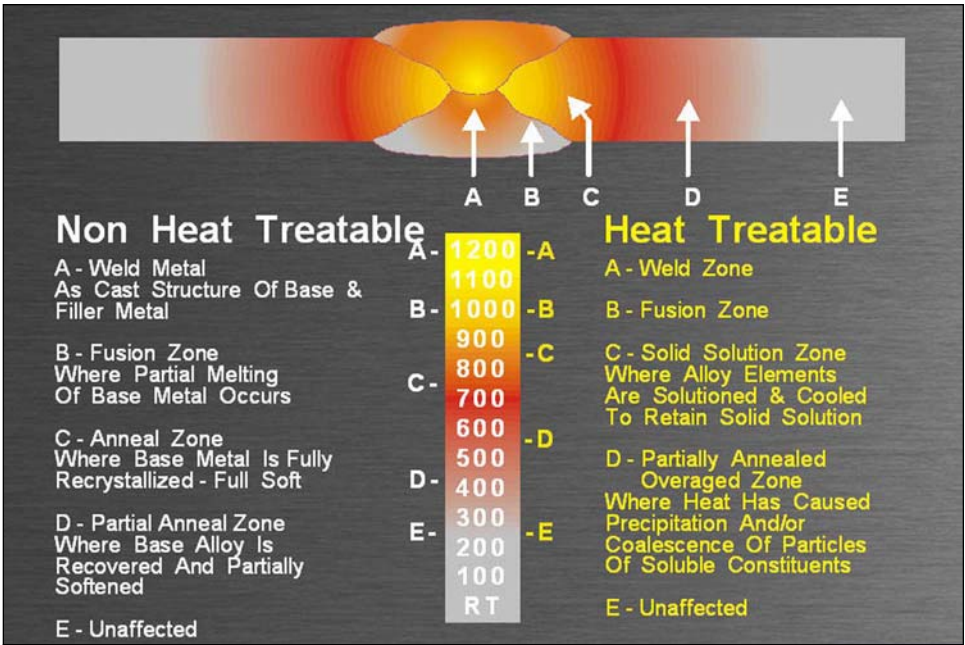


Figure 3.1—Shows the HAZ on Both the Heat-Treatable and Nonheat-Treatable Alloys

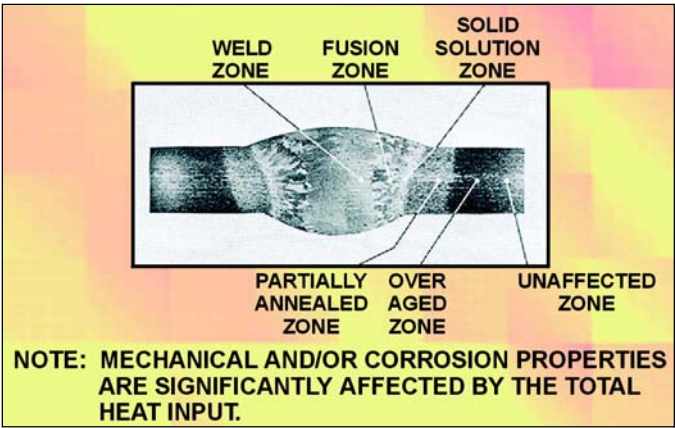


Figure 3.2—The Welding Heat Affect on a Heat-Treatable Alloy

3.2.15 Nonheat-Treatable Alloys

What is important from a HAZ perspective is that aluminum alloys strengthened by strain hardening can be restored to a full soft, ductile condition by annealing. Annealing eliminates the strain hardening, as well as the microstructure that is developed because of cold working. The heating of the HAZ, which takes place during the arc welding operation, is sufficient to anneal the base material within the HAZ area. For this reason the minimum tensile strength requirements for as-welded nonheat-treatable alloys is based on the annealed strength of the base alloy. Typical tensile strengths of nonheat-treatable alloys in their tempered condition and as-welded are shown in Table 3.6.

Table 3.6—Typical Tensile Strength Properties of Groove Welds—Nonheat-Treatable Alloys

Base Alloy and Temper	Base Alloy Tensile Strength		As-Welded Tensile Strength	
	ksi	MPa	ksi	MPa
1060-H18	19	131	10	69
5052-H32	33	228	27	186
5052-H39	42	290	27	186
5086-H34	47	324	38	262
5086-H38	53	365	38	262
5083-H116	46	317	43	296
3003-H34	35	241	16	110
3004-H38	41	283	24	165

3.2.16 Heat-Treatable Alloys

In the case of the heat-treatable alloys, the HAZ will not be fully annealed. Typically, the HAZ is not maintained at an adequate temperature for a sufficient period to anneal fully the HAZ. This does not suggest that experiences in a reduction in strength in the HAZ will not occur. The affect on the HAZ of a heat-treatable alloy that is welded in the solution heat-treated and artificially aged condition is typically one of partially annealed and over-aged. This condition is affected by the heat input during the welding operation. The general rule is, the higher the heat input, the lower the as-welded strength. Typical tensile strengths of some of the heat-treatable alloys in their temper condition and as-welded are shown in Table 3.7.

3.2.17 Conclusion

Dependant on the particular aluminum alloy type and its temper, there are often significant difference between the tensile strength of the HAZ and the tensile strength of the unaffected area of the welded component. The reduction in tensile strength of the

Table 3.7—Typical Tensile Strength Properties
of Groove Welds—Heat-Treatable Alloys

Base Alloy and Temper	Base Alloy Tensile Strength		As-Welded Tensile Strength	
	ksi	MPa	ksi	MPa
6063-T6	31	214	19	131
6061-T6	45	310	27	186
6061-T4	35	241	27	186
2219-T81	66	455	35	241
2014-T6	70	483	34	234
7005-T53	57	393	43	296

HAZ under controlled conditions, particularly with the nonheat-treatable alloys, can be somewhat predictable. The reduction in tensile strength of the HAZ in the heat-treatable alloys is more susceptible to welding conditions and strength can be reduced below the required minimum requirement if excessive heating occurs during the welding operation.

3.3 Is There a Filler Alloy that Can be Used to Weld All Aluminum Base Alloys, and How Do I Weld Aluminum Alloys 7075 and 2024?

 I work in a small welding repair shop and am often asked to perform repair welding on aluminum structures. Sometimes I know the base metal type and sometimes I don't. I have two questions relating to repairing aluminum. First, is there a filler metal that can be used to successfully weld all types of aluminum alloys? Second, I come into contact, from time to time, with two aluminum alloys that are difficult to obtain arc welding information about. These alloys are 2024 and 7075. Can you provide some information on how to weld these alloys with either the gas metal arc or gas tungsten arc welding processes?

3.3.1 A Filler Alloy for All Aluminum Base Alloys

With regard to your first question, the short answer is there is no filler metal that is suitable for welding all types of aluminum alloys. There are currently close to 500 wrought aluminum alloys and more than 250 aluminum alloys in the form of castings and ingots registered with The Aluminum Association. The alloy chemical composition limits for all these registered alloys are contained in The Aluminum Association's

teal-colored book titled *International Alloy Designations and Chemical Composition Limits for Wrought Aluminum and Wrought Aluminum Alloy*” and in its pink-colored book titled *Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot*.

Aluminum alloys can be categorized into a number of groups based on the particular material’s characteristics, such as its ability to respond to thermal and mechanical treatment and the primary alloying element added. Probably the most important consideration encountered during repair operations is identification of the base metal type. If the base material type is not available through a reliable source, it can be difficult to select a suitable welding procedure.

There are some guides as to the most probable type of aluminum used in different applications. For example, most extruded aluminum is 6xxx series (Al-Mg-Si). In the automotive industry, air-conditioning systems and heat exchangers are typically made from 3003 sheet and 6061 tubing. Car wheels are often made from 5454, which, because of its controlled magnesium (less than 3% Mg), is suitable for temperature applications. Ship hulls are often manufactured from 5083 (5% Mg), which is recognized as a marine material.

Unfortunately, there is no guarantee. If the base material type is not known, or unavailable, the only reliable way to establish the exact type of aluminum alloy is through chemical analysis. A small sample of the base material must be sent to a reliable aluminum testing laboratory and a chemical analysis performed. Generally, the chemistry can then be evaluated and a determination made regarding the most suitable filler metal and welding procedure. Be aware that incorrect assumptions about the chemistry of an aluminum alloy can seriously affect the welding results.

3.3.2 Welding 2024 and 7075

In response to the second question, the reason you are having difficulty finding information on welding 2024 and 7075 is because both materials belong to a small group of aluminum alloys generally considered to be unweldable by arc welding. These materials are often found in aircraft, sporting equipment, and other types of high-performance, safety-critical equipment and are not usually arc welded on the original component. Probably the two most commonly found aluminum alloys within this category are 2024, which is an aluminum-copper-magnesium alloy, and 7075, which is an aluminum-zinc-copper-magnesium alloy. Both materials can become susceptible to stress corrosion cracking after welding. This phenomenon is particularly dangerous because it is not detectable immediately after welding, but usually develops at a later date when the component is in service. The completed weld joint can appear to be of excellent quality immediately after welding. However, changes that occur within the base material adjacent to the weld during the welding process can produce a metallurgical condition that results in intergranular microcracking, which may be susceptible to propagation and cause failure of the welded component. Failure probability can be high, and the time to failure is generally unpredictable and dependent on variables such as tensile stress applied to the joint, environmental conditions, and the period of time the component is subjected to these variables.

I strongly recommend great care be taken in considering the repair of components made from these materials. It must be stressed that arc welding repairs should not be performed on these alloys and they should not be returned to service if there is

any possibility of a weld failure becoming the cause of damage or injury to person or property.

3.3.3 Conclusion

In answer to your first question, and as discussed above, there is no filler metal suitable for welding all aluminum base alloys. The answer to your second question, the reason you can not find any information on how to weld 7075 and 2024 base alloys is that both of these materials are not suitable for arc welding.

3.4 What are the Differences Between the Heat-Treatable and Nonheat-Treatable Aluminum Alloys?



I have often heard the terms Heat-Treatable and Nonheat-Treatable Aluminum Alloys. What are the differences between these alloys, and how does the type of base alloy affect the final strength of the weld?

3.4.1 Understanding the Basic Differences Between Heat-Treatable and Nonheat-Treatable Aluminum Alloys

Heat-Treatable and Nonheat-Treatable are the two basic types of aluminum alloys. They are both widely used in welding fabrication and have somewhat different characteristics associated with their chemical and metallurgical structure, and their reactions during the arc welding process.

To best answer the question, we first need to understand the basic differences between these two groups of alloys.

3.4.2 Nonheat-Treatable Aluminum Alloys

The strength of these alloys is initially produced by alloying the aluminum with additions of other elements. These alloys consist of the pure aluminum alloys (1xxx series), manganese alloys (3xxx series), silicon alloys (4xxx series) and magnesium alloys (5xxx series). A further increase in strength of these alloys is obtained through various degrees of cold working or strain hardening. Cold working or strain hardening is accomplished by rolling, drawing through dies, stretching or similar operations where area reduction is obtained. Regulating the amount of total reduction in area of the material controls its final properties. Material which has been subjected to a strain-hardening temper, may also be given a final, elevated temperature treatment called “stabilizing,” to ensure that the final mechanical properties do not change over time.

The letter “H” followed by numbers denotes the specific condition obtained from strain hardening.

The first number following the “H” indicates the basic operations used during or after strain hardening:

H1—Strain hardened only

H2—Strain hardened and partially annealed

H3—Strain hardened and stabilized

The second number following the “H” indicates the degree of strain hardening:

HX2—Quarter Hard

HX4—Half Hard

HX6—Three-Quarter Hard

HX8—Full Hard

HX9—Extra Hard

3.4.3 Heat-Treatable Aluminum Alloys

The initial strength of these alloys is also produced by the addition of alloying elements to pure aluminum. These elements include copper (2xxx series), magnesium and silicon, which is able to form the compound magnesium silicide (6xxx series), and zinc (7xxx series). When present in a given alloy, singly or in various combinations, these elements exhibit increasing solid solubility in aluminum as the temperature increases. Because of this reaction, it is possible to produce significant additional strengthening to the heat-treatable alloys by subjecting them to an elevated thermal treatment, quenching, and, when applicable, precipitation heat-treatment known also as artificial aging.

NOTE: Because of additions of magnesium and or copper, there are also a number of silicon (4xxx series) alloys that are heat-treatable.

In solution heat-treatment, the material is typically heated to temperatures of 900°F to 1050°F [482°C to 566°C], depending upon the alloy. This causes the alloying elements within the material to go into solid solution; rapid quenching, usually in water, which freezes or traps the alloying elements in solution, follows this process.

Precipitation heat-treatment or artificial aging is used after solution heat-treatment. This involves heating the material for a controlled time at a lower temperature (around 250°F to 400°F [121°C to 204°C]). This process, used after solution heat-treatment, both increases strength and stabilizes the material.

3.4.4 How Does the Type of Material, Heat-Treated or Nonheat-Treated, Affect the Completed Strength of the Weld?

In short, the difference in transverse tensile strength of the completed groove weld is governed by the reaction of the base material to the heating and cooling cycles during the welding operation.

Generally speaking, the nonheat-treatable alloys are annealed in the heat-affected zone adjacent to the weld. This is unavoidable when arc welding, as we will reach the annealing temperature, and extended time at these temperatures is not required to anneal the base material.

The heat-treatable alloys are usually not fully annealed during the welding operation but are subjected to a partial anneal and overaging process. These alloys are very susceptible to time at temperature; the higher the temperature and the longer at that temperature, the more significant the loss of strength in the base material adjacent to the weld. For this reason, it is important to control the overall heat input, preheating, and interpass temperatures when welding the heat-treatable alloys.

Typically, the common heat-treatable base alloys, such as 6061-T6, lose a substantial proportion of their mechanical strength after welding. For example, 6061-T6 typically has 45 000 psi tensile strength prior to welding and around 27 000 psi in the as-welded condition. One option with the heat-treatable alloys is postweld heat-treatment to return the mechanical strength to the manufactured component. If postweld heat-treating is considered, the filler alloy's ability to respond to the heat-treatment should be evaluated.

Most of the commonly used filler alloys will not respond to postweld heat treatment without substantial dilution with the heat-treatable base alloy. This is not always easy to achieve and can be difficult to control consistently. For this reason, filler alloys have been developed to independently respond to heat-treatment.

As an example, filler alloy 4643 was developed for welding 6xxx series base alloys and developing high mechanical properties in the postweld heat-treated condition. This alloy was developed by taking the well-known alloy 4043, reducing the silicon, and adding 0.10% to 0.30% magnesium, thus ensuring its ability to unquestionably respond to postweld heat-treatment.

3.4.5 Conclusion

The primary difference between the nonheat-treatable and the heat-treatable aluminum alloys is associated with the methods used to change the mechanical properties of these materials. Both materials can be affected by the heat generated during the arc welding process. The affect of heating during welding is usually more predictable on the nonheat-treatable alloys than it is on the heat-treatable alloys.

3.5 What are the Alloying Elements in Aluminum Alloys?



I have been informed that pure aluminum is not usually used for structural applications and that to produce aluminum that is of adequate strength for the manufacture of structural components, it is necessary to add other elements to the aluminum. What elements are added to these aluminum alloys? What affect do they have on the material's performance? And in what applications are these alloys used?

3.5.1 The Addition of Alloying Elements to Aluminum

Your acquired information is essentially correct. It would be very unusual to find pure aluminum (1xxx series of alloys) chosen for structural fabrication because of their