Preface xi

1	Introduction 1
	Further Reading 6
2	Categorization of Welding and Weld Problems 7
2.1	What Is Welding? 7
2.2	Microstructural Zones of Welds 13
2.3	Origin of Problems in Welding and Welds 19
2.4	How Problems Can Be Logically Categorized? 20
	References 21
	Further Reading 21
	Part I Manifestation of Problems with Welds and
	Weldments 23
3	Problems with Joint Setup and Weld Joints 25
3.1	Joint Efficiency 25
3.2	Weld Joint Types and Weld Configurations 26
3.3	Joint Setup Problems 31
3.4	Problems with Weld Profile 35
3.5	Troubleshooting Guide 42
	References 45
	Further Reading 45
	3
4	Shape Distortion, Dimensional Shrinkage, and Geometric
	Instability 47
4.1	Thermal Versus Mechanical Stresses in a Structure 47
4.2	Residual Stresses Versus Distortion 48
4.3	Origin and Effect of Volumetric Shrinkage 48
4.4	Origin and Effect of Thermal Contraction 52
4.5	Problems from Nonuniform Thermal Contraction and CTE
	Mismatches 57

4.6	Problems from Distortion and from Residual Stresses 60
4.7	Distortion Control and Residual Stress Reduction 60
4.8	Troubleshooting Guide 65
	References 65
	Further Reading 66
	Turther rouding 00
5	Porosity 67
5.1	The Most Common Problem in Welds 67
5.2	Types of Weld Porosity 70
5.3	Gases in Molten Weld Metal 73
5.4	The Many Possible Causes of Porosity in Welds 79
5. 4 5.5	Attempting to Minimize Porosity Formation in Fusion Welds 84
5.6	- •
5.0	,,
	References 87
	Further Reading 87
6	Cracks 89
6.1	The Most Dreaded Defect in Welds 89
6.2	Classification of Cracking and Cracks in Welds and Welding 90
6.3	Hot Cracking and Cracks 91
	•
6.4	Cold Cracking and Cracks 98
6.5	Other Weld-Related Cracking and Cracks 101
6.6	Crack-Prone Metals and Alloys 102
6.7	Troubleshooting Cracking Problems in Welds 105
	References 106
	Further Reading 107
7	Nonmetallic and Metallic Inclusions 109
7.1	Solid Versus Gas Inclusions 109
7.1	Nonmetallic Inclusions in Welds 110
7.3	Metallic Inclusions in Welds 114
7.4	Troubleshooting Problems with Inclusions in Welds 115
	References 116
	Further Reading 116
8	Weld Appearance 117
8.1	
	, 0
8.2	Weld Crown Bead Faults 118
8.3	Weld Root Bead Faults 121
8.4	Fillet Weld Faults 123
8.5	Reading Weld Ripple Marks 124
8.6	Weld Spatter 126
8.7	Arc Strikes 128
8.8	Weld Heat Tint 129
8.9	Troubleshooting Weld Appearance Problems 132
	References 133
	Further Reading 134
	•

Part II Location of Problems in Welds 135

9	Fusion Zone of Fusion Welds 137
9.1	A Refresher on Microstructural Zones in and Around Welds 137
9.2	Gas Porosity in the Fusion Zone of Welds 141
9.3	Cracking in the Fusion Zone of Welds 143
9.4	Inclusions in the Fusion Zone of Welds 151
9.5	Macrosegregation in the Fusion Zone of Welds 152
9.6	Troubleshooting Problems in the Fusion Zone of Welds 153
	References 155
	Further Reading 156
10	Partially Melted Zone of Fusion Welds 157
10.1	Origin and Location of the PMZ in Fusion Welds 157
10.2	Conventional Hot Cracking in the PMZ 161
10.3	Constitutional Liquation Cracking in the PMZ 161
10.4	Cold Cracking in the PMZ 164
10.5	Overcoming Cracking Problems in the PMZ 166
10.6	Troubleshooting Problems in the PMZ 167
	References 167
•	Further Reading 168
11	Heat-Affected Zone of Fusion Welds 169
11.1	Origin and Location of the HAZ for Fusion Welds 169
11.2	Manifestation of Problems in the HAZ of Fusion Welds 170
11.3	Precipitation-Hardening Alloy HAZ Problems 171
11.4	Sensitization in the HAZ of Austenitic Stainless Steels 176
11.5	Transformation-Hardening Steel HAZ Problems 179
11.6	Reheat Cracking 183
11.7	Troubleshooting Problems in the HAZ of Fusion Welds 186
	References 187
	Further Reading 188
12	Unaffected Base Metal Cracking Associated with Welding $\;\;189$
12.1	Weld-Related Problems in the Unaffected Base Metal 189
12.2	Lamellar Tearing in Thick Steel Weldments 189
12.3	Corrosion Cracking Caused by Fusion Welding 192
12.4	Fatigue Cracking Outside Fusion Welds 195
12.5	Troubleshooting Weld-Related Problems in the Unaffected Base
	Metal 199
	References 200
	Further Reading 201
13	Discontinuities in Multi-pass Welds 203
13.1	Needs for Multi-pass Welding and Welds 203
13.2	Various Functions of Multi-pass Welding and Welds 205

13.3	Defects Found in Multi-pass Welds 207
13.4	Composition Adjustment with Multi-pass Welding 210
13.5	Property Alteration with Multi-pass Welding 213
13.6	Troubleshooting Problems in Multi-pass Welding and Welds 216
	References 217
	Further Reading 217
14	Problems with Non-fusion Welding and Non-fusion
141	Welds 219
14.1	Non-fusion Welding Processes Versus Fusion Welding
140	Processes 219
14.2	Overview of Non-fusion Processes 220
14.2.1	Pressure Welding Processes 222
14.2.2	Friction Welding Processes 222
14.2.3	Diffusion Welding Processes 222
14.2.4	Solid-State Deposition Welding 223
14.3	Problems with Non-fusion Welds and Non-fusion Welding
	Processes 223
14.4	Inspection and Repair Challenges with Non-fusion Welds 229
14.5	Troubleshooting Problems with Non-fusion Welds 230
	References 230
	Further Reading 231
	Part III Material-Specific Weld-Related Problems 233
15	
15	Embrittlement of Carbon and Low- and Medium-alloy
	Embrittlement of Carbon and Low- and Medium-alloy Steels 235
15.1	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235
15.1	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy
15.1 15.2	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238
15.1 15.2 15.3	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239
15.1 15.2 15.3 15.4	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240
15.1 15.2 15.3 15.4 15.5	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241
15.1 15.2 15.3 15.4 15.5	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245 Further Reading 245
15.1 15.2 15.3 15.4 15.5 15.6	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245 Further Reading 245 Sensitization or Weld Decay and Knife-line Attack in Stainless Steels 247
15.1 15.2 15.3 15.4 15.5 15.6 15.7	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245 Further Reading 245 Sensitization or Weld Decay and Knife-line Attack in Stainless Steels 247 A Primer on the Metallurgy of Stainless Steels 247
15.1 15.2 15.3 15.4 15.5 15.6 15.7	Embrittlement of Carbon and Low- and Medium-alloy Steels 235 The Importance of Steel 235 Four Causes of Embrittlement in Carbon and Low- and Medium-alloy Steels 238 Hydrogen Embrittlement: A Misnomer in Steels 239 Secondary Hardening in Steels 240 Ductile-to-Brittle Transition in Steels 241 Compromise of Fatigue and Impact Behavior by Residual Stresses in Steels 243 Troubleshooting Problems from Embrittlement of Steels by Welding 244 References 245 Further Reading 245 Sensitization or Weld Decay and Knife-line Attack in Stainless Steels 247

16.4	Knife-line Attack in Stabilized Austenitic Stainless Steels 252
16.5	Troubleshooting Problems from Sensitization or Knife-line
	Attack 254
	References 255
	Further Reading 255
17	Stress Relief Cracking of Precipitation-Hardening Alloys 257
17.1	Different Names, Same Phenomenon 257
17.2	Stress Relief Cracking in Ferritic Alloy Steels 260
17.3	Stress Relaxation Cracking in Stainless Steels 265
17.4	Strain-age Cracking in Ni-Based Superalloys 267
17.5	Troubleshooting Problems from Stress Relief or Strain-age
	Cracking 270
	References 271
	Further Reading 271
18	Loss of Properties in Cold-Worked Metals and Alloys 273
18.1	Cold Work, Recovery, Recrystallization, and Grain Growth 273
18.2	Cold-Worked Metals and Alloys in Engineering 278
18.3	Avoiding or Recovering Properties Loss from Fusion Welding 281
18.4	The Worked Zone in Pressure-Welded Metals and Alloys 284
18.5	Troubleshooting Welding Problems in Cold-Worked Metals and
	Alloys 285
	References 285
	Further Reading 286
19	Embrittlement with High-chromium Contents 287
19.1	Phase Formation and Structure 287
19.2	Adverse Effects of σ -Phase 291
19.3	Susceptible Alloys 291
19.4	Guidelines for Avoiding or Resolving Problems from σ-Phase 293
19.5	Troubleshooting Problems with σ-Phase Associated with
	Welding 294
	References 295
	Further Reading 295
20	Wold Dilution and Chamical Inhomographity, 207
20 20.1	Weld Dilution and Chemical Inhomogeneity 297 The Designer's Druthers 297
20.1	Chemical Inhomogeneity in Welds 300
20.2	Weld Dilution 302
20.3	The Unmixed Zone in the Weld Metal 304
20.4	Impurities in the Weld Metal 307
20.6	Troubleshooting Problems from Weld Dilution and Chemical
20.0	Inhomogeneity 307
	References 308
	Further Reading 308
	Turnier reduing 500

21	Dissimilar Metal and Alloy Welding 309
21.1	Joining Dissimilar Materials 309
21.2	The Need for Welding Dissimilar Metals and Alloys 311
21.3	Chemical Incompatibility 311
21.4	Mechanical Incompatibility 315
21.5	Thermal Incompatibility 315
21.6	Troubleshooting Problems with Dissimilar Metal and Alloy
	Welding 318
	References 318
	Further Reading 319

Closing Thoughts 321

Index 323