Contents

Preface v Prologue xi FUSION WELDING - PROCESS VARIABLES 1 1. Fusion welding 2Principles of consumable development 4 Absorption of gases in the weld metal 9Nitrogen absorption 10 Hydrogen absorption 11 Composition of welds 12 Summary of process variables 17 The weld thermal cycle 17 Heat-flow equations 17 The thermal cycle of the base metal 23 Refinements to the heat-flow equations 26 Heat flow in electroslag welding 28 Weld simulation 29 Summary of weld thermal cycle results 33 Residual stresses in welds 33 Stresses and strains generated by changes in temperature 33 Stresses generated by the $\gamma \rightarrow \alpha$ phase transformation 36 Measurement of residual stresses in welds 39 Numerical methods of estimating residual stresses in welds 42 Summary of residual stress work 44 References 46 Further reading 47 2. THE WELD METAL 48 Characteristics of weld solidification 49 Geometry of the weld melt 49 Epitaxial solidification 56 Crystal growth and segregation 59 No diffusion in solid; perfect mixing in liquid 60° No diffusion in solid; diffusional mixing in liquid 62

Cellular and dendritic solidification in welds 66 Refining weld structures 73 Phase transformations during cooling of the weld metal 75 Kinetics of phase transformations 75 Transformations in duplex stainless steel welds 83 Transformations in carbon and low alloy steel welds 88 Role of alloving in transformation kinetics 93 Role of slag inclusions in transformation kinetics 96 Predicting the microstructure and properties of weld metals 99 References 102 Further reading 103 THE HEAT-AFFECTED ZONE 104 3. The base material 105 The base metal's carbon equivalent 110 The heating cycle 112 Recrystallization 113 The $\alpha \rightarrow \gamma$ phase transformation 114 Precipitate stability 115 Precipitate coarsening during a weld thermal cycle 118 Precipitate dissolution during a weld thermal cycle 121 Grain growth 123 Kinetics of grain growth 123 Grain growth during welding, assuming particle dissolution 126 Grain growth during welding, assuming particle coarsening 130 Practical considerations of grain growth and grain growth control in the HAZ 132 Reactions at the fusion line 138 Transformations during cooling 141 Grain growth zone 141 Grain refined zone 141 Partially transformed zone 143 Zone of spheroidized carbides 143 Zone of 'unchanged' base material 143 Predicting the microstructure and properties of the HAZ 143 Weld simulation 144 Hardness measurements 144 Weld CCT diagrams 147 Weld microstructure diagrams 148 Grain growth diagrams 148 Multi-run welds 150 The weld metal 151 The HAZ 151 References 154 Further reading 155 4. CRACKING AND FRACTURE IN WELDS 156 Fracture toughness 156 Fracture toughness testing 160

Solidification cracking 164 Solidification structure 164 Segregation 166 Residual stresses and joint geometry 168 Mechanism of solidification cracking 168 Liquation cracking 170 Lamellar tearing 172 Mechanism of lamellar tearing 174 Cold cracking 180 Role of hydrogen 181 Role of stress 185 Role of microstructure 187 Mechanism of cold cracking 190 Reheat cracking 194 Effect of reheating on the microstructure of a 0.5Cr-Mo-V alloy 197 Mechanism of reheat cracking 200 Case study: The Alexander Kielland disaster 203 Construction of the Alexander Kielland 206 The construction and fitting of the sonar flange plate 206 Capsize of the Alexander Kielland 209 Metallographic examination of the sonar flange plate welds 212 Possible effects of the weld thermal cycle on the bracing and flange plate materials 215 Mechanism of failure: main conclusions 218 References 219 Further reading 220 APPENDIX: Weld cracking tests and weldability formulae 223 INDEX 227