

Contents

Preface XVII

List of Contributors XIX

Introduction 1
Jürgen Hirsch (Editor)

Part I	Main Al Alloys & Products	5
	Industrial Processing and Typical Applications	
1	DC Casting	7
	Microstructure and General Specifications	
	<i>Wolfgang Schneider and Gerd-Ulrich Grün</i>	
1.1	Introduction	7
1.2	Overview on Microstructure Related Specifications of As-cast Material	7
1.3	Structural Parameters in D.C. Casting of Aluminium and Aluminium Alloys	8
1.4	Summary	12
	References	12
2	Al 99,5 for Packaging and Foil Applications	13
	EN-AW 1xxx Performance Requirements for Foil Products & Relationship to Microstructure, Alloy Composition and Processing	
	<i>Richard Hamerton</i>	
2.1	Product Description	13
2.2	Material Quality Requirements	15
2.3	Aluminium Alloy Class and Chemical Compositions	15
2.4	Mechanical Properties at Final Gauge	15
2.5	Typical Process Route for DC Cast EN-AW 1200 Foil Products	16
2.6	Relationship of Performance to Microstructure and Processing	16
2.6.1	Microstructural Features Controlling Product Performance	16

2.6.2	Effect of Composition and Processing on Microstructure of EN-AW 1200	18
	References	18
3	Al-Mn Brazing Sheet for Heat Exchangers	19
	EN AW-3xxx Processing, Microstructure, and Properties	
	<i>Hans-Erik Ekström</i>	
3.1	Product Description	19
3.2	Aluminium Alloy Class and Chemical Compositions	20
3.3	Material Quality Requirements	20
3.3.1	Brazeability	21
3.3.2	Mechanical Strength	22
3.3.3	Formability	22
3.3.4	Corrosion Resistance	22
3.4	Production Route and Process Details	23
3.5	Current Status of Knowledge on Microstructure Evolution and Properties	24
	References	26
4	AlMn1Mg1 for Beverage Cans	27
	EN-AW 3104 Processing, Microstructure, Simulation and Property Control	
	<i>Jürgen Hirsch</i>	
4.1	Product Description	27
4.2	Material Requirements	28
4.3	Aluminium Alloys Used and Chemical Compositions	28
4.4	Quality Parameters	29
4.5	Production Route and Process Details	31
4.5.1	DC-ingot Casting	32
4.5.2	Homogenization	32
4.5.3	Hot Rolling	33
4.5.4	Cold Rolling	34
4.5.5	Annealing/Paint Baking	34
4.6	Simulation of Microstructure Evolution and Properties	35
	References	36
5	Al-Mg Sheet for Automotive and Architectural Applications	37
	EN-AW 5xxx Processing, Microstructure, Simulation and Property Control	
	<i>Tim J. Hurd and Menno R. van der Winden</i>	
5.1	Product Description	37
5.2	Material Quality Requirement	37
5.3	Aluminium Alloy Class and Chemical Compositions	39
5.4	Quality Parameters and Typical Customer Specifications for EN-AW 5005	40

5.4.1	Mechanical Properties	40
5.4.2	Grain Structure	41
5.4.3	Earing/Texture	41
5.4.4	Electrical and Thermal Properties	42
5.4.5	Corrosion Properties	42
5.4.6	Joining Properties	42
5.5	Production Route and Process Details	43
5.5.1	DC-ingot Casting	44
5.5.2	Preheating/Homogenisation	44
5.5.3	Hot Rolling	44
5.5.4	Cold Rolling	44
5.5.5	Annealing and Interannealing	45
5.5.6	Further Processing	45
5.6	Microstructure /Properties Relationships	45
5.7	Simulation of Microstructure Evolution and Properties	48
5.8	Summary	48
	References	49
6	Al-Mg-Si Sheet Alloys for Autobody Applications	51
	EN AW-6xxx Processing, Microstructure and Property Control	
	<i>Eike Brünger, Olaf Engler and Jürgen Hirsch</i>	
6.1	Product Description	51
6.2	Aluminium Alloy Class and Chemical Compositions	53
6.3	Material Quality Requirements	54
6.3.1	Stamping and Hemming Performance	54
6.4	Surface Appearance after Forming	56
6.5	Strength after Bake Hardening	57
6.6	Production Route and Process Details	58
	References	61
7	Extrusions from Heat Treatable Alloys	65
	EN AW-6063, EN AW-6082 and EN AW-7108 –	
	Processing, Microstructure, Simulation and Property Control	
	<i>Tanja Pettersen and Trond Furu</i>	
7.1	Product Description and Applications	65
7.2	Material (Quality) Requirements and Typical Customer Specifications	67
7.3	Aluminium Alloy Class and Chemical Compositions	67
7.4	Production Route and Process Details	68
7.5	Microstructure Effects and Properties	69
7.5.1	EN-AW 6063	69
7.5.1.1	Thermo-mechanical Processing	70
7.5.1.2	The As-deformed Material	72
7.5.1.3	Recrystallized Material	73
7.5.2	EN-AW 6082	75

7.5.2.1	The As-deformed Material	75
7.5.3	EN-AW 7108	78
7.6	Modelling Flow Stress, Recrystallization, Microstructures and Textures	79
	References	81

Part II Material Models 83
Integrated Process Simulations

8 Physical Metallurgy 85

Fundamentals of Through-Process Modelling

Günter Gottstein

8.1	The Problem	85
8.2	Homogenization	86
8.2.1	Thermodynamics	86
8.2.2	Diffusion	88
8.3	Roughing or Break-down Rolling	91
8.4	Hot Rolling	92
8.4.1	Crystal Plasticity	92
8.4.1.1	Dislocations	92
8.4.1.2	Hardening Mechanisms	93
8.5	Recovery	96
8.6	Recrystallization	97
8.6.1	Introduction	97
8.6.2	Influence of Solutes and Particles	100
8.7	Grain Growth	103
8.8	Texture	106
8.9	Cold Rolling	108
8.10	Back Annealing	109
8.11	Summary	109
	References	110

9 Solidification Microstructures in Aluminium Alloys 111

Review of Modelling Approaches

Alain Jacot

9.1	Introduction	111
9.2	Modelling of Grain Structures on the Process Scale	112
9.2.1	The Deterministic Approach	112
9.2.2	The Stochastic Approach	113
9.2.3	Modelling the Grain Structure in DC Casting of Aluminium	115
9.2.4	The VIRCAST Model	115
9.3	Modelling of Internal Grain Structures	116
9.3.1	The Primary Phase Formation	117

9.3.2	The Phase Field Method	118
9.3.3	Level Set and Pseudo-front Tracking Methods	120
9.3.4	The VIRCAS ^T Primary Phase Model	120
9.3.5	The Formation of Interdendritic Phases	121
9.3.6	The VIRCAS ^T Secondary Phase Model	122
9.4	Conclusion	125
	Acknowledgments	125
	References	126
10	Work Hardening of Aluminium Alloys	129
	A Review of Selected Work Hardening Models	
	<i>Bjørn Holmedal, Erik Nes and Knut Marthinsen</i>	
	Abstract	129
10.1	Introduction	129
10.2	Review of Models	131
10.2.1	The MTS-model	131
10.2.2	The MMP-model	133
10.2.3	The 3IV-model	136
10.2.4	Other Models	138
10.3	Discussion and Application	139
10.3.1	The Flow Stress Models	140
10.3.2	Athermal Storage of Dislocations	141
10.3.3	Dynamic Recovery	141
10.3.4	The Different Stages of Work Hardening	143
10.3.5	Modelling Work Hardening and Hot Deformation Behaviour of Aluminium Alloys	147
10.4	Summary	153
	Acknowledgements	153
	References	154
11	Recovery, Recrystallization and Grain Growth	157
	Review of Softening Models	
	<i>Günter Gottstein</i>	
11.1	Introduction	157
11.2	Phenomenological Models	158
11.3	Geometrical Microstructure Models	159
11.4	Vertex Models	161
11.5	Discrete Models	163
11.6	Recovery	167
11.6.1	Dislocation Rearrangement	167
11.6.2	Subgrain Coarsening	168
11.7	Texture Models	169
11.8	Summary	173
	References	173

12	Simulation of Deformation Textures	177
	A Review of Latest Grain-interaction Models	
	<i>Paul Van Houtte, Saiyi Li and Olaf Engler</i>	
	Abstract	177
12.1	Introduction	177
12.2	Description of Models	178
12.3	Model Validation	183
12.4	Discussion and Conclusions	185
	Acknowledgments	187
	References	188
13	Simulation of Sheet Anisotropy	189
	Polycrystal-plasticity Simulation of Earing Profiles from Texture Data	
	<i>Olaf Engler, Jürgen Hirsch and Stefan Kalz</i>	
	Abstract	189
13.1	Introduction	189
13.2	Polycrystal-plasticity Modelling of Earing Profiles	191
13.3	Application of the Earing Model and Assessment of the Predictions	193
13.3.1	VIR[FORM] Sheet Alloys	193
13.3.2	EN-AW 3104 Can Body Stock	194
13.3.3	PSN Texture with 25°/70° Earing Profiles	195
13.4	Discussion and Conclusions	196
	Acknowledgments	197
	References	198
14	Modelling Microchemistry	199
	Simulation of Alloy Effects in Aluminium	
	<i>Alexis Miroux, Rias (Z.J.) Lok, Erica Anselmino and Sybrand van der Zwaag</i>	
14.1	Introduction	199
14.2	Microchemistry Interaction with Microstructure and Mechanical Properties	200
14.2.1	Interaction Mechanisms and Important Parameters to Exchange	200
14.2.1.1	Solutes and Precipitates Influence on Work-hardening	200
14.2.1.2	Solutes and Precipitates Influence on Recovery and Recrystallisation	201
14.2.1.3	Influence of the Microstructure on Precipitation	202
14.2.2	Examples of Systems and Processes where Coupling is Necessary	203
14.3	Microchemistry Models	204
14.3.1	Thermodynamic Models	204
14.3.2	Models at the Atomic Scale	205
14.3.3	Classical Analytical Models	205
14.3.4	Model with a Mesoscopic Spatial Resolution	208

14.4	Integrated Modelling	208
14.5	Conclusion	210
	References	211
15	Rolling of Aluminium – 1	213
	Thermomechanical Processing and FEM Simulation	
	<i>Jesús Talamantes-Silva, John H. Beynon and Christophe Pinna</i>	
15.1	Introduction	213
15.1.1	Thermomechanical Processing: The Need for a Better Understanding	213
15.2	Thermomechanical Processing of Aluminium Alloys	214
15.2.1	Hot Rolling	214
15.2.2	Cold Rolling	215
15.2.3	Thermomechanical Processing (TMP)	215
15.2.4	Primary Concepts of Hot Rolling	216
15.2.4.1	The Arc of Contact and the Angle of Bite	216
15.2.4.2	Reduction, Elongation and Spread	217
15.2.4.3	Friction and the Neutral Zone	218
15.2.4.4	Relative Slip	218
15.2.4.5	Pressure and Shear Stress Distribution	219
15.2.4.6	Force, Torque, and Power	219
15.2.5	Constitutive Equations and Flow Stress for Hot Rolling	222
15.2.5.1	Determination of Flow Curves	222
15.2.5.2	The Influence of Temperature and Strain Rate	223
15.2.5.3	Common Relationships for Flow Stress During Rolling	224
15.2.5.4	A Simple Relationship to Evaluate the Stress During Rolling	225
15.3	The Tool-stock Interface	225
15.3.1	Introduction	225
15.3.2	Friction	226
15.3.2.1	The Influence of Friction	226
15.3.2.2	Friction Theories	226
15.3.2.3	Importance of Lubrication	227
15.3.3	Heat Transfer Phenomena	228
15.3.3.1	Heat Generation During Rolling	229
15.3.3.2	Heat Conduction within the Stock	229
15.3.3.3	Heat Lost Through Free Surfaces During Rolling	230
15.3.3.4	Thermal Resistance at the Interface	230
15.3.3.5	Process and Material Parameters Affecting the Thermal Interface	232
15.4	Thermomechanical Processing Using the Finite Element Method	232
15.4.1	Introduction	232
15.4.2	Numerical Methods in Continuum Mechanics	233
15.4.2.1	The Finite Difference Method (FD)	233
15.4.2.2	The Boundary Element Approach (BE)	234
15.4.2.3	The Finite Element Approach (FE)	234
15.4.3	Basics of Finite Element Theory	235

15.4.3.1	Background to the Finite Element Method	235
15.4.3.2	Basic Steps in the Finite Element Analysis	235
15.4.3.3	Linear FE Analysis	237
15.4.3.4	Non-linear FE Analysis	237
15.4.3.5	Finite Element Formulations	238
15.4.3.6	Origin of Non-linearity	239
15.4.3.7	The Integration Scheme: Implicit vs Explicit	241
15.4.3.8	Friction Contact	242
15.4.4	Finite Element Formulation for Heat Transfer	243
15.4.5	The Need for Thermo-mechanical Coupling	244
15.4.6	Closing Remarks	244
	References	245
16	Rolling of Aluminium – 2	247
	Practical Aspects for Finite Element Model Development	
	<i>Jesus Talamantes-Silva and John H. Beynon</i>	
16.1	Introduction	247
16.1.1	Thermo-mechanical Coupling	247
16.2	Selecting an Appropriate Finite Element Code	248
16.2.1	Codes Available for this Study	248
16.3	The Finite Element Code	248
16.4	Modelling Approach to Hot Rolling	249
16.4.1	Modelling a Multi-pass Rolling Mill: An Industrial Example	249
16.4.2	Modelling a Multi-pass Research Mill: Experimental Trials	260
16.4.3	Modelling Breakdown and Finishing Rolling: Industrial Case	268
16.5	Closing Remarks	274
17	Forming Simulation	275
	Numerical Simulation and Material Models of Aluminium Sheet Forming	
	<i>Dorel Banabic and A. Erman Tekkaya</i>	
	Abstract	275
17.1	Introduction	275
17.2	History of Numerical Simulation Methods	276
17.3	Industrial Requirements to Simulation of Sheet Metal Forming	278
17.4	Various Approaches of Approximate Analysis	280
17.4.1	Element Types	280
17.4.2	Quasi-static Implicit Approach	281
17.4.3	Dynamic Explicit Approach	281
17.4.4	Inverse Approach (One-Step-Methods)	283
17.5	Current State	283
17.6	Material Models	286
17.6.1	BBC Yield Criteria	288
17.6.2	Yld2000-2d Yield Criterion	289
17.6.3	Cazacu-Barlat Yield Criterion (CB2001)	290

17.6.4	Validation of the Phenomenological Yield Criteria or two Aluminium Alloys	290
17.7	Prediction of Forming Limit	292
17.7.1	Swift Model	293
17.7.2	Hill Model	293
17.7.3	Marciniak-Kuczynski Model	294
17.7.4	Linear Perturbation Theory	296
17.7.5	Empirical Models for the FLC Calculation	296
17.8	Expected Future Developments	297
17.9	Conclusions	298
	References	299
Part III	Model Application and Simulation Exercises	303
	The “VIRFAB TPM Trials”	
18	The VIR[*] Projects	305
	A European EAA R&D Initiative 2000–2004	
	<i>Menno R. van der Winden, Gerd-Ulrich Grün, Trond Furu and Kolstein Asboell</i>	
18.1	Introduction	305
18.2	The VIR[*] Projects	305
18.2.1	VIR[CAST]	306
18.2.2	VIR[FAB]	308
18.2.3	VIR[FORM]	309
18.3	Conclusions	310
	Acknowledgments	310
	References	311
19	Challenges for Through Process Modelling	315
	Property Simulation Requirements for Conventional Aluminium Alloys and Products	
	<i>Kai F. Karhausen and Jürgen Hirsch</i>	
19.1	Challenges for Integrated Process and Microstructure Simulation	315
19.2	Modelling of Resulting Properties	318
20	Through Process Simulation of EN AW-5182 Sheet Production	323
	Integrated Simulation of Microstructure and Resulting Properties	
	<i>Kai F. Karhausen, Mischa Crumbach, Luc Neumann, Jürgen Hirsch, Matthias Goerdeler, Günter Gottstein and Reiner Kopp</i>	
	Abstract	323
20.1	Introduction	323
20.2	Background and Coupling of Sub-models for Through Process Modelling (TPM)	324

20.2.1	Thermal/Mechanical Models (Larstran/Shape, RoseRoll and RoseTem)	324
20.2.2	Models for Work Hardening and Dynamic Softening (3IVM and 4IVM)	326
20.2.3	Tracing of State Variables (Strucsim)	327
20.2.4	Full Constraints Taylor Texture Model	327
20.2.5	Grain Interaction Texture Model (GIA)	328
20.2.6	Static Recrystallisation Texture Model (StaRT) with Nucleation Texture Model (ReNuc)	329
20.3	Vertical Macro-micro Model Integration	329
20.4	Integrated Thermo-mechanical Simulation of Sheet Fabrication Processes	330
20.5	Simulation of Microstructure, Texture and Resulting Properties	334
20.6	Conclusions	340
	Acknowledgments	341
	References	341
21	Through Process Simulation of EN AW-3103 Sheet Production	343
	Modelling the Evolution of Microstructure, Texture, Microchemistry and Mechanical Properties	
	<i>Knut Marthinsen, Shariar Abtahi, Bjørn Holmedal, Erik Nes, Arve Johansen, Trond Furu, Olaf Engler, Zacharias J. Lok, Alexis Miroux and Jesus Talamantes-Silva</i>	
	Abstract	343
21.1	Introduction	343
21.2	Presentation of Sub-models	345
21.2.1	Solidification and Homogenization	345
21.2.2	Deformation Sub-structure and Work Hardening	345
21.2.3	Recovery and Recrystallization	346
21.2.4	Microchemistry	346
21.2.5	Deformation and Recrystallization Textures	347
21.2.6	FEM and Coupling of Sub-models	348
21.3	Through Process Modelling	348
21.3.1	Casting, Homogenization and Preheating	349
21.3.2	Multi-pass Hot Rolling	349
21.3.3	Coil Cooling and Cold Rolling	354
21.3.4	Final Annealing	356
21.3.5	Mechanical Properties	358
21.3.6	Forming and Formability	359
21.4	Discussion and Conclusions	359
	Acknowledgments	361
	References	361

22	Through Process Simulation of Extrusion	363
	Modelling the Evolution of Microstructure and Mechanical Properties through the Process Chain	
	<i>Trond Furu, Anne Lise Dons, Torodd Berstad, Bjørn Holmedal and Knut Marthinsen</i>	
	Abstract	363
22.1	Introduction	363
22.2	Modelling Approach	364
22.3	Through Process Modelling (TPM), Application and Discussion	365
22.3.1	As Cast Microstructure	366
22.3.2	As Homogenised Microstructure	367
22.3.3	Flow Stress and Substructure during and after Extrusion	369
22.3.4	Deformation Texture after Extrusion	371
22.3.5	Recrystallization Grain Structure after Extrusion	371
22.3.6	Forming of the Extruded Profiles	373
22.4	Concluding Remarks	375
	Acknowledgments	375
	References	376
	Subject Index	377

