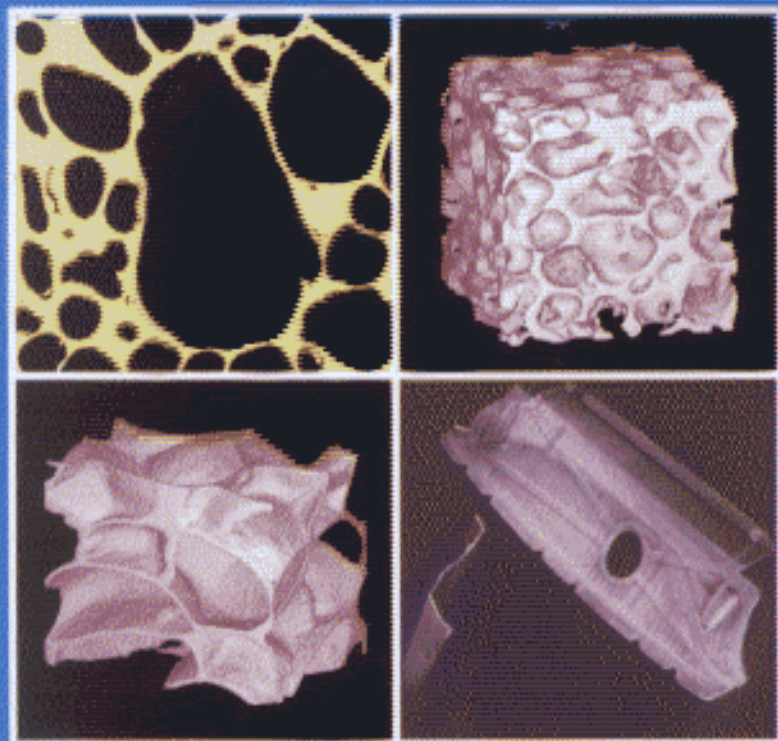


Handbook of Cellular Metals

Production, Processing, Applications

Edited by Hans-Peter Degischer
and Brigitte Kriszt



Contents

1	Introduction: The Strange World of Cellular Metals	1
2	Material Definitions, Processing, and Recycling	5
2.1	Foaming Processes for Al	8
2.1.1	Gas Injection: the Cymat/Alcan and Norsk Hydro Process	8
2.1.2	<i>In-situ Gas Generation: the Shinko Wire Process and the FORMGRIP process</i>	10
2.1.2.1	The Shinko Wire Process [2]	10
2.1.2.2	The FORMGRIP Process	12
2.2	Industrialization of Powder-Compact Foaming Technique	14
2.2.1	Principles of Foam Production	14
2.2.2	Practical Aspects of Foam Production	17
2.2.2.1	Powder selection	17
2.2.2.2	Mixing	18
2.2.2.3	Densification	18
2.2.2.4	Further processing of foamable material	19
2.2.2.5	Foaming	19
2.2.3	State of Commercialization	20
2.3	Making Cellular Metals from Metals other than Aluminum	21
2.3.1	Zinc	22
2.3.2	Lead	22
2.3.3	Titanium	22
2.3.4	Steel	25
2.3.4.1	Powder-Compact Foaming Technique	25
2.3.4.2	Steel Foams from Powder-Filler Mixtures	27
2.4	Recycling of Cellular Metals	28
2.4.1	The Remelting of Cellular Metals	28
2.4.2	Recycling of Cellular Metal Matrix Composites	29
2.4.3	Conclusions	32
2.5	The Physics of Foaming: Structure Formation and Stability	33
2.5.1	Isolated Gas Bubble in a Melt	34
2.5.2	Agglomeration of Bubbles: Foam	35

2.6	Infiltration and the Replication Process for Producing Metal Sponges	43
2.6.1	Replication	44
2.6.2	The Replication Process: General Principles	46
2.6.2.1	Pattern Preparation	46
2.6.2.2	Infiltration	48
2.6.2.3	Pattern Removal	49
2.6.3	Physical and Mechanical Properties of Metal Sponge	51
2.6.3.1	Continuous Refractory Patterns	51
2.6.3.2	Discontinuous Refractory Patterns	51
2.6.3.3	Burnable Patterns	53
2.6.3.4	Leachable Patterns	53
2.6.4	Conclusions	55
2.7	Solid-State and Deposition Methods	56
2.7.1	Formation from Single Cells: Coreless Methods	58
2.7.1.1	Hollow-Sphere Structures made from Gas Atomized Hollow Powders	58
2.7.1.2	Hollow-Sphere Structures made from Coaxially Sprayed Slurries	59
2.7.2	Formation from Single Cells: Lost Core Methods	60
2.7.2.1	Hollow-Sphere Structures made by Cementation and Sintering	60
2.7.2.2	Hollow-Sphere Structures made from Galvanically Coated Styrofoam Spheres	61
2.7.2.3	Hollow-Sphere Structures made from Fluidized Bed Coated Styrofoam Spheres	61
2.7.3	Bulk Formation: Coreless Methods	63
2.7.3.1	Sintered Metal Powders and Fibers	63
2.7.3.2	Methods Utilizing Special Sintering Phenomena	64
2.7.3.3	Foaming of Solids	65
2.7.3.4	Foaming of Slurries	67
2.7.4	Bulk Formation: Lost Core Methods	67
2.7.4.1	Powder Metallurgical Space Holder Method	67
2.7.4.2	Deposition Methods	68
3	Secondary Treatment of Cellular Metals	71
3.1	Forming, Machining, and Coating	75
3.1.1	High-Temperature Forming	75
3.1.1.1	Specific Problems in Foam Forming	75
3.1.1.2	Process Sequence for Manufacturing 3D Composites with Aluminum Foam Cores	76
3.1.1.3	Material Behavior at the Solidus	77
3.1.1.4	Forming of Cellular Metals at High Temperatures	78
3.1.2	Machining	79
3.1.3	Coating	79
3.1.3.1	Mechanical Properties of Spray Deposits	80
3.1.3.2	Specific Difficulties in Foam Coating	80

3.1.3.3	Thermal Sprayed Composites from Metal Foams	81
3.2	Joining Technologies for Structures Including Cellular Aluminum	83
3.2.1	Introduction	83
3.2.2	Feasible Joining Technologies	83
3.2.2.1	Mechanical Fastening Elements	83
3.2.2.2	Gluing	84
3.2.2.3	Welding	84
3.2.2.4	Soldering and Brazing	85
3.2.3	Foam–Foam Joints	87
3.2.4	Foam–Sheet Joints	87
3.2.4.1	Microstructural Investigations	88
3.2.4.2	Mechanical Properties of Foam–Sheet Joints	90
3.2.5	Transferability to Structural Parts	98
3.2.5.1	Tubes	98
3.2.5.2	Hat-Profiles	99
3.2.6	Summary	100
3.3	Encasing by Casting	103
3.3.1	Foam Cores for Encasing by Casting	103
3.3.1.1	Core Production	103
3.3.1.2	Core Attachment	104
3.3.1.3	Mechanical Properties	105
3.3.1.4	Coating of the Foam Cores	106
3.3.2	Shell Casting Processes	107
3.3.2.1	High-Pressure Casting Processes	107
3.3.2.2	Bonding Between Shell and Foam Core	112
3.4	Sandwich Panels	113
3.4.1	Sandwich Foaming Process	114
3.4.2	Industrial Application	116
3.4.2.1	Technological Benefits	117
3.4.2.2	Technical Limitations	118
3.4.3	Joining Technology of AFS	119
3.4.3.1	Laser Welding	120
3.4.3.2	TIG/MIG Welding	120
3.4.3.3	Bolt/Pin Welding	121
3.4.3.4	Punch Riveting	122
3.4.3.5	Riveting Nuts and Screws	123
3.4.3.6	Flow Drilling	123
3.4.3.7	Riveting	123
3.4.3.8	Bonding	123
3.4.4	Cutting of AFS	124
3.4.4.1	Laser Beam Cutting	124
3.4.4.2	Water Jet Cutting	124

4	Characterization of Cellular Metals	127
4.1	Characterization of Cellular and Foamed Metals	130
4.1.1	Definition of Structural Features of a Cellular Metal and Influence on Property Profile	130
4.1.1.1	Density and Volume Fraction of Pores	131
4.1.1.2	Shape and Size of Pores	133
4.1.2	Characterization Methods and Quantities of Geometric Architecture of Real Metallic Foams	136
4.1.2.1	Sample Preparation	136
4.1.2.2	Pore Size	137
4.1.2.3	Pore Shape	139
4.1.2.4	Pore Orientation	140
4.1.2.5	Thickness of Cell Edges and Walls	140
4.1.2.6	Topological Features	141
4.1.3	Characterization of Microstructure of Massive Cell Material	141
4.1.4	Conclusions	143
4.2	Computed X-ray Tomography	145
4.2.1	Principle of the Technique	145
4.2.1.1	X-ray Radiography	145
4.2.1.2	X-ray Tomography	146
4.2.2	Set-ups	147
4.2.2.1	Medium-Resolution Microtomography	147
4.2.2.2	High-Resolution Microtomography	147
4.2.2.3	Resolution Required for the Study of Metallic Foams	148
4.2.2.4	Reconstruction Method	148
4.2.3	Experimental Results	148
4.2.3.1	Initial Cell Structure	148
4.2.3.2	Evolution of the Structure During a Compression Test	150
4.2.4	Micromodeling of a Foam by Finite Elements	151
4.2.4.1	Direct Meshing of the Actual Microstructure	151
4.2.4.2	Results	152
4.2.5	Conclusions	155
4.3	Considerations on Quality Features	156
4.3.1	Introduction	156
4.3.2	Non-Uniformity of Cellular Metals	156
4.3.3	Macroscopic Parameters	159
4.3.3.1	Type of Cellular Metal	159
4.3.3.2	Surface and Dimensions	159
4.3.3.3	Apparent Density	161
4.3.3.4	Properties	161
4.3.4	Microscopic Features	161
4.3.4.1	Microstructure of the Metal	162
4.3.4.2	Geometrical Features	162
4.3.4.3	Microdefects	164
4.3.5	Mesosopic Features	165

4.3.5.1	Geometry of Cellular Structure	165
4.3.5.2	Density Distribution	166
4.3.6	Systematics of Quality Features	166
4.3.7	Approximation of a Cellular Structure by a Continuum	168
4.3.7.1	Calculation of Density Maps	168
4.3.7.2	Representation of Non-Uniformity of Densities	172
4.3.7.3	Mesoscopic Basis for Material Modeling	174
4.3.8	Proposal of Quality Criteria	174
5	Material Properties	179
5.1	Mechanical Properties and Determination	183
5.1.1	Young's Modulus	183
5.1.1.1	Influence of the Foam Structure	184
5.1.1.2	Influence of the Foam Density	185
5.1.1.3	Influence of Deformation	186
5.1.2	Compression Behavior	187
5.1.3	Energy-Absorbing and Impact Behavior	190
5.1.3.1	Energy Absorbing Capability	190
5.1.3.2	Impact Behavior	191
5.1.4	Tension Behavior	193
5.1.4.1	General Tensile Behavior	193
5.1.4.2	The Influence of Notches	195
5.1.4.3	Foam-Specific Test Problems in Tension	196
5.1.5	Torsion Behavior	196
5.1.6	Fracture Behavior	197
5.1.6.1	Crack Initiation and Crack Propagation	197
5.1.6.2	Fracture Toughness	198
5.1.6.3	Foam-Specific Test Problems	201
5.2	Fatigue Properties and Endurance Limit of Aluminum Foams	203
5.2.1	Literature Survey of Endurance Data	203
5.2.2	High Cycle Fatigue Properties and Endurance Limit	208
5.2.2.1	Material and Procedure	208
5.2.2.2	Results	209
5.2.3	Mechanism of Crack Initiation	210
5.2.4	Summary	214
5.3	Electrical, Thermal, and Acoustic Properties of Cellular Metals	215
5.3.1	Electrical Properties	215
5.3.2	Thermal Properties	221
5.3.3	Acoustic Properties	225
5.3.3.1	Materials for Sound Insulation	226
5.3.3.2	Sound Absorbing Materials	228
5.3.3.3	Structural Damping	236

6	Modeling and Simulation	243
6.1	Modeling of Cellular Metals	245
6.1.1	Motivation	246
6.1.2	Micromechanical Modeling of Cellular Materials: Basics	247
6.1.2.1	Analytical and Numerical Models	247
6.1.2.2	Classification of Microgeometries	249
6.1.2.3	Information Obtainable from Micromechanics	251
6.1.3	Selected Results of Micromechanical Simulations	252
6.1.3.1	Influence of Material Distribution in the Cell Walls	252
6.1.3.2	Influence of Wavy and Curved Cell Walls	255
6.1.3.3	Influence of Irregular Vertex Positions	257
6.1.3.4	Microgeometries Containing Cells of Different Sizes	258
6.1.3.5	Influence of Holes and Solid-Filled Cells	260
6.1.3.6	Influence of Fractured or Removed Cell Walls	261
6.1.3.7	Yield and Collapse Surfaces	262
6.1.3.8	Fracture Simulations for Metallic Foams	266
6.1.4	Modeling of Mesoscopic Density Inhomogeneities	269
6.1.5	Macroscopic Modeling and Simulation	272
6.1.5.1	Low Energy Impact on Thin Metallic Foam Paddings	273
6.1.5.2	Crushing of Foam-Filled Crash Elements	275
6.1.6	Design Optimization for Cellular Metals	276
6.1.7	Outlook	277
6.2	Mesomodel of Real Cellular Structures	281
6.2.1	Introduction	281
6.2.2	3D Mesomodel	284
6.2.2.1	Elastic Regime	285
6.2.2.2	Plastic Regime	285
6.2.3	Modeling of Uniaxial Compression	288
6.2.3.1	Deformation Band	289
6.2.3.2	Mechanical Properties	292
6.2.4	Discussion	294
6.2.5	Conclusions	297
7	Service Properties and Exploitability	299
7.1	The Range of Applications of Structural Foams Based on Cellular Metals and Alternative Polymer Solutions	299
7.1.1	Introduction	299
7.1.2	Potential Areas of Use	300
7.1.3	Material Properties	300
7.1.4	Main Component Configurations	301
7.1.5	Application and Attachment Techniques	304
7.1.5.1	Casting	304
7.1.5.2	Thermal Joining Processes	305
7.1.5.3	Mechanical Joining Processes	306
7.1.5.4	Three-dimensional sandwich	306

7.1.5.5	Alternative Cellular Materials Based on Polymers	306
7.1.6	Effectiveness	307
7.1.6.1	Bending and Torsional Stress	307
7.1.6.2	Impact Stresses	308
7.1.6.3	Axial Load	309
7.1.6.4	Acoustics	310
7.1.7	Outlook	311
7.2	Functional Applications	313
7.2.1	General Considerations	313
7.2.2	Biomedical Implants	314
7.2.3	Filtration and Separation	315
7.2.4	Heat Exchangers and Cooling Machines	315
7.2.5	Supports for Catalysts	317
7.2.6	Storage and Transfer of Liquids	317
7.2.7	Fluid Flow Control	317
7.2.8	Silencers	318
7.2.9	Spargers	318
7.2.10	Battery Electrodes	318
7.2.11	Electrochemical Applications	319
7.2.12	Flame Arresters	319
7.2.13	Water Purification	319
7.2.14	Acoustic Control	319
7.3	Machinery Applications	320
7.3.1	Parameters	321
7.3.1.1	Thermal Behavior	321
7.3.1.2	Pull-Out Strength of Detachable Joints	322
7.3.2	Examples of Application	323
7.3.2.1	Foamed Steel Pipes	323
7.3.2.2	Machine Table	327
7.3.2.3	Cross-Slide	329
7.3.3	Conclusions	330
7.4	Prototypes by Powder Compact Foaming	330
7.4.1	Introduction	331
7.4.2	Methods, Machines, and Molds	332
7.4.2.1	Manufacturing Methods for Precursor Material	333
7.4.2.2	Foaming Process	334
7.4.2.3	Foaming Furnaces	334
7.4.2.4	Foaming Molds	336
7.4.3	Prototypes and their Applications	337
7.4.3.1	Automotive Applications	338
7.4.3.2	Construction and Architecture	340
7.4.3.3	Other Technical Applications	340
7.4.3.4	Improbable Applications	343

7.5	Applying the Investment Methodology for Materials (IMM) to Aluminum Foams	346
7.5.1	Introduction: The Investment Methodology for Materials (IMM)	346
7.5.2	Initial Market Scan for Potential Applications for Al Foams	347
7.5.3	Material Assessment	347
7.5.3.1	Technical Performance	347
7.5.3.2	Cost of Production	348
7.5.3.3	Co-Minimizing Volume and Cost in Energy-Absorbing Applications	349
7.5.4	Market Forecast	350
7.5.4.1	Market Size for Aluminum Foam	350
7.5.4.2	Market Timing for Aluminum Foams	350
7.5.5	Value Capture	351
7.5.5.1	Industry Structure	351
7.5.5.2	Appropriability of Profits	352
7.5.6	Conclusions: Applying IMM to Aluminum Foams	353
8	Strengths, Weaknesses, and Opportunities	355
8.1	Processing	355
8.2	Properties	358
8.3	Design and Application	360