
MAGNESIUM, MAGNESIUM ALLOYS, AND MAGNESIUM COMPOSITES

Manoj Gupta
Nai Mui Ling Sharon



A JOHN WILEY & SONS, INC. PUBLICATION

CONTENTS

PREFACE	xv
ACKNOWLEDGMENTS	xvii
1 INTRODUCTION TO MAGNESIUM	1
1.1 Introduction	1
1.2 Characteristics of Pure Magnesium	4
1.2.1 Atomic Properties and Crystal Structure	4
1.2.2 Physical Properties	4
1.2.3 Electrical Properties	4
1.2.4 Mechanical Properties	5
1.3 Applications	5
1.3.1 Automotive Applications	5
1.3.2 Aerospace Applications	7
1.3.3 Medical Applications	8
1.3.4 Sports Applications	9
1.3.5 Electronic Applications	10
1.3.6 Other Applications	10
1.4 Summary	11
References	11
2 SYNTHESIS TECHNIQUES FOR MAGNESIUM-BASED MATERIALS	13
2.1 Introduction	13
2.2 Liquid Phase Processes	14
2.2.1 Sand Casting	14
2.2.2 Die Casting	15
2.2.3 Squeeze Casting	16
2.2.4 SSM Casting	17
2.2.4.1 <i>Thixomolding</i>	17
2.2.4.2 <i>Rheocasting</i>	18
2.2.5 Stir Casting	18
2.2.6 Spray Forming	19
2.2.7 Melt Infiltration Method	20
2.2.8 <i>In Situ</i> Synthesis	21

2.3	Solid Phase Process	21
2.3.1	Blending	21
2.3.2	Mechanical Alloying	23
2.3.3	Powder Consolidation (Compaction)	24
2.3.4	Sintering Methods	26
	2.3.4.1 <i>Conventional Sintering</i>	28
	2.3.4.2 <i>Microwave Sintering</i>	29
2.4	Disintegrated Melt Deposition Method	32
2.5	Mechanical Disintegration and Deposition Method	35
2.6	Summary	36
	References	36

3 MAGNESIUM ALLOYS 39

3.1	Introduction	39
3.1.1	Effects of Addition of Metallic Elements on Magnesium	40
	3.1.1.1 <i>Aluminum</i>	40
	3.1.1.2 <i>Beryllium</i>	40
	3.1.1.3 <i>Calcium</i>	40
	3.1.1.4 <i>Cerium</i>	40
	3.1.1.5 <i>Copper</i>	40
	3.1.1.6 <i>Iron</i>	40
	3.1.1.7 <i>Lithium</i>	40
	3.1.1.8 <i>Manganese</i>	41
	3.1.1.9 <i>Molybdenum</i>	41
	3.1.1.10 <i>Nickel</i>	41
	3.1.1.11 <i>Rare Earth Metals (RE)</i>	41
	3.1.1.11.1 <i>Neodymium</i>	41
	3.1.1.12 <i>Silicon</i>	41
	3.1.1.13 <i>Silver</i>	41
	3.1.1.14 <i>Strontium</i>	41
	3.1.1.15 <i>Thorium</i>	42
	3.1.1.16 <i>Tin</i>	42
	3.1.1.17 <i>Titanium</i>	42
	3.1.1.18 <i>Yttrium</i>	42
	3.1.1.19 <i>Zinc</i>	42
	3.1.1.20 <i>Zirconium</i>	42
3.1.2	Classifications of Magnesium Alloys	42
	3.1.2.1 <i>Alloy Designations</i>	42
	3.1.2.2 <i>Temper Designations</i>	43
3.2	Casting Alloys	44
	3.2.1 <i>Characteristics of Casting Alloys</i>	44
	3.2.2 <i>Physical Properties of Casting Alloys</i>	44
	3.2.3 <i>Mechanical Properties of Casting Alloys</i>	47

3.3	Wrought Alloys	47
3.3.1	Characteristics of Wrought Alloys	47
3.3.2	Mechanical Properties of Wrought Alloys	47
3.4	Magnesium Elektron Series Alloys	55
3.4.1	Magnesium Elektron Casting Alloys	55
3.4.2	Wrought Magnesium Elektron Alloys	56
3.5	Magnesium Alloys for Elevated Temperature Applications	62
3.5.1	Mg–Al–RE Alloys	63
3.5.2	Mg–Al–Ca Alloys	65
3.5.3	Mg–Al–Ca–RE Alloys	66
3.5.4	Mg–Zn–Al–Ca Alloys	72
3.5.5	Mg–Al–Sr Alloys	72
3.5.6	Mg–Al–Si Alloys	76
3.5.7	Mg–RE–Zn Alloys	76
3.5.8	Summary—Creep Strength	76
3.6	Magnesium-Based Bulk Metallic Glasses	76
	References	81
4	FUNDAMENTALS OF METAL MATRIX COMPOSITES	87
4.1	Introduction	87
4.1.1	Factors Affecting Properties of MMCs	88
4.2	Materials	89
4.2.1	Matrix	90
4.2.2	Reinforcements	90
4.3	Interface Between Matrix and Reinforcement	94
4.3.1	Tailoring the Interface for Enhanced Performance	95
4.3.2	Methods of Interface Engineering	96
4.3.3	Tailoring the Interface Through Choice of Processing Technique	96
4.3.4	Interfacial Failure	96
4.4	Theoretical Prediction of Properties	97
4.4.1	Density	97
4.4.2	Electrical Conductivity	97
4.4.2.1	<i>Rayleigh–Maxwell Equation</i>	97
4.4.2.2	<i>Kerner's Model</i>	98
4.4.2.3	<i>ROMs Model</i>	98
4.4.3	Coefficient of Thermal Expansion	99
4.4.3.1	<i>ROMs (Upper Bound)</i>	99
4.4.3.2	<i>Turner's Model (Lower Bound)</i>	99
4.4.3.3	<i>Kerner's Model</i>	100
4.4.4	Elastic Modulus	100
4.4.4.1	<i>Rule of Mixtures</i>	100
4.4.4.2	<i>Halpin–Tsai Model</i>	101
4.4.4.3	<i>Effect of Porosity on Elastic Modulus</i>	101

4.4.5	Yield Strength	102
4.4.5.1	<i>Shear Lag Theories</i>	102
4.4.5.2	<i>Strengthening Factors</i>	103
4.4.5.2.1	<i>Thermal and Elastic Modulus Mismatch</i>	103
4.4.5.2.2	<i>Load-bearing Effect</i>	104
4.4.5.2.3	<i>Orowan Strengthening</i>	105
4.4.5.2.4	<i>Hall–Petch Effect</i>	105
4.4.6	Ductility	105
4.5	Summary	107
	References	107

5 MAGNESIUM COMPOSITES 113

5.1	Introduction	113
5.2	Materials	114
5.2.1	Matrix	114
5.2.2	Reinforcements	114
5.2.2.1	<i>Type of Reinforcements</i>	114
5.2.2.2	<i>Shape of Reinforcements</i>	116
5.2.2.3	<i>Amount of Reinforcements</i>	116
5.2.2.4	<i>Length Scale of Reinforcements</i>	116
5.2.2.5	<i>Ductility Effects of Reinforcements</i>	118
5.3	Magnesium-Based Composites with Al_2O_3	121
5.3.1	Addition of Sub-Micrometer-Size Al_2O_3	122
5.3.1.1	<i>Mg Reinforced with 0.3 μm Al_2O_3 (by Disintegrated Melt Deposition)</i>	122
5.3.1.2	<i>Mg Reinforced with 0.3 μm Al_2O_3 (by Powder Metallurgy—Microwave Sintering)</i>	123
5.3.2	Addition of Nanosize Al_2O_3	124
5.3.2.1	<i>Mg Reinforced with 50 nm Al_2O_3 (by Disintegrated Melt Deposition)</i>	124
5.3.2.2	<i>Mg Reinforced with 50 nm Al_2O_3 (by Powder Metallurgy—Conventional Sintering)</i>	125
5.3.2.3	<i>Mg Reinforced with 50 nm Al_2O_3 (by Powder Metallurgy—Microwave Sintering)</i>	126
5.3.2.4	<i>AZ31B Reinforced with 50 nm Al_2O_3 (by Disintegrated Melt Deposition)</i>	127
5.3.2.5	<i>AZ31B Reinforced with 50 nm Al_2O_3 and with Ca addition (by Disintegrated Melt Deposition)</i>	128
5.3.2.6	<i>AZ31 Reinforced with 50 nm Al_2O_3 (by Disintegrated Melt Deposition)</i>	129
5.3.3	Addition of Hybrid Reinforcements (with Al_2O_3)	130
5.3.3.1	<i>Mg Reinforced with Al_2O_3 of Different Sizes (by Powder Metallurgy—Conventional Sintering)</i>	130

5.3.3.2	<i>Mg Reinforced with Al₂O₃ of Different Size (by Powder Metallurgy—Microwave Sintering)</i>	131
5.3.3.3	<i>Mg Reinforced with Mg-NanoAl₂O₃ Concentric Alternating Macro Ring (by Powder Metallurgy—Microwave Sintering)</i>	132
5.3.3.4	<i>Mg Reinforced with Al₂O₃ and MWCNT (by Powder Metallurgy—Microwave Sintering)</i>	133
5.4	Magnesium-Based Composites with MgO	134
5.4.1	Addition of Nanosize MgO	135
5.4.1.1	<i>Mg Reinforced with 36 nm MgO (by Disintegrated Melt Deposition)</i>	135
5.5	Magnesium-Based Composites with SiC	136
5.5.1	Addition of Micrometer-Size SiC	136
5.5.1.1	<i>Mg and AZ91D Reinforced with 150 μm SiC (by Stir Casting)</i>	136
5.5.1.2	<i>Mg and AZ91 Reinforced with 100 μm SiC (by Liquid Infiltration)</i>	137
5.5.1.3	<i>Mg Reinforced with 40 μm SiC (by Melt Stir Technique)</i>	138
	(a) Tested at Room Temperature	138
	(b) Tested at Elevated Temperatures	139
5.5.1.4	<i>Mg Reinforced with 38 μm SiC (by Disintegrated Melt Deposition)</i>	139
	(a) Effect of Extrusion Temperature	140
	(b) Effect of Heat Treatment	141
	(c) Effect of Recycling	142
5.5.1.5	<i>Mg Reinforced with 35 μm SiC (by Conventional Casting)</i>	143
5.5.1.6	<i>Mg Reinforced with 25 μm SiC (by Disintegrated Melt Deposition)</i>	144
5.5.1.7	<i>Mg Reinforced with 25 μm SiC (by Conventional Casting)</i>	145
5.5.1.8	<i>Mg–Al Reinforced with 20 μm SiC (by Powder Metallurgy)</i>	146
	(a) Liquid-Phase Sintering	146
	(b) Solid-Phase Sintering	147
5.5.1.9	<i>AZ91C Reinforced with 12.8 μm SiC (by Vacuum Stir Casting)</i>	148
5.5.2	Addition of Sub-Micrometer-Size SiC	149
5.5.2.1	<i>Mg Reinforced with 0.6 μm SiC (by Disintegrated Melt Deposition)</i>	149
	(a) Effect of Heat Treatment	150
5.5.3	Addition of Nanosize SiC	151

5.5.3.1	<i>Mg Reinforced with 50 nm SiC (by Melt Casting—Ultrasonic Cavitation)</i>	151
5.5.3.2	<i>Mg4Zn Reinforced with 50 nm SiC (by Melt Casting—Ultrasonic Cavitation)</i>	152
5.5.3.3	<i>Mg6Zn Reinforced with 50 nm SiC (by Melt Casting—Ultrasonic Cavitation)</i>	153
	<i>(a) As-Cast Condition</i>	153
	<i>(b) Heat-Treated Condition (T5)</i>	154
5.5.3.4	<i>Mg Reinforced with 45–55 nm SiC (by Powder Metallurgy)</i>	155
	<i>(a) Without Sintering Process</i>	155
	<i>(b) Hybrid Microwave-Assisted Sintering</i>	156
5.5.4	<i>Addition of Hybrid Reinforcement (with SiC)</i>	157
5.5.4.1	<i>Mg Reinforced with SiC of Different Sizes (by Powder Metallurgy—Microwave Sintering)</i>	157
5.5.4.2	<i>Mg Reinforced with 50 nm Al₂O₃ and 50 nm SiC (by Powder Metallurgy—Microwave Sintering)</i>	158
5.5.4.3	<i>Mg Reinforced with 50 nm SiC and MWCNT (by Powder Metallurgy—Microwave Sintering)</i>	159
5.6	<i>Magnesium-Based Composites with Y₂O₃</i>	160
5.6.1	<i>Addition of Nanosize Y₂O₃</i>	160
5.6.1.1	<i>Mg Reinforced with 29 nm Y₂O₃ (by Disintegrated Melt Deposition)</i>	160
5.6.1.2	<i>Mg Reinforced with 29 nm Y₂O₃ (by Powder Metallurgy—Conventional Sintering)</i>	162
5.6.1.3	<i>Mg Reinforced with 32–36 nm Y₂O₃ (by Disintegrated Melt Deposition)</i>	163
5.6.1.4	<i>Mg Reinforced with 30–50 nm Y₂O₃ (by Powder Metallurgy—Microwave Sintering)</i>	164
	<i>(a) Effect of Amount of Y₂O₃ Addition</i>	164
	<i>(b) Effect of Heating Rate</i>	165
	<i>(c) Effect of Extrusion Ratio</i>	165
5.6.2	<i>Addition of Hybrid Reinforcements (with Y₂O₃)</i>	166
5.6.2.1	<i>Mg Reinforced with Y₂O₃ and Nanosize Cu (by Powder Metallurgy—Microwave Sintering)</i>	166
5.6.2.2	<i>Mg Reinforced with Y₂O₃ and Nanosize Ni (by Powder Metallurgy—Microwave Sintering)</i>	167
5.7	<i>Magnesium-Based Composites with ZrO₂</i>	168
5.7.1	<i>Addition of Nanosize ZrO₂</i>	168
5.7.1.1	<i>Mg Reinforced with 29–68 nm ZrO₂ (by Disintegrated Melt Deposition)</i>	168
5.7.1.2	<i>Mg Reinforced with 29–68 nm ZrO₂ (by Powder Metallurgy—Conventional Sintering)</i>	169
5.8	<i>Magnesium-Based Composites with CNT</i>	170

5.8.1	Addition of MWCNTs	171
5.8.1.1	<i>Mg Reinforced with MWCNTs (by Disintegrated Melt Deposition)</i>	171
5.8.1.2	<i>Mg Reinforced with MWCNTs (by Powder Metallurgy—Conventional Sintering)</i>	172
5.8.1.3	<i>AZ91D Reinforced with MWCNTs (by Powder Metallurgy—Mechanical Milling)</i>	173
5.8.1.4	<i>AZ91D Reinforced with MWCNTs (by Melt Stirring Method)</i>	174
5.8.1.5	<i>AZ31 Reinforced with CNTs (by Disintegrated Melt Deposition)</i>	175
	(a) Tensile Test	175
	(b) Compression Test	176
5.9	Magnesium-Based Composites with Metallic Additions	176
5.9.1	Addition of Micrometer-Size Copper	177
5.9.1.1	<i>Mg Reinforced with 8–11 μm Cu (by Disintegrated Melt Deposition)</i>	177
5.9.1.2	<i>AZ91A Reinforced with 8–11 μm Cu (by Disintegrated Melt Deposition)</i>	178
5.9.1.3	<i>AZ91A and Mg Reinforced with 8–11 μm Cu (by Disintegrated Melt Deposition)</i>	179
5.9.2	Addition of Nanosize Copper	180
5.9.2.1	<i>Mg Reinforced with 50 nm Cu (by Powder Metallurgy—Microwave Sintering)</i>	180
5.9.3	Addition of Nickel	181
5.9.3.1	<i>Mg Reinforced with Micrometer-Size Ni (by Disintegrated Melt Deposition)</i>	181
5.9.4	Addition of Titanium	183
5.9.4.1	<i>Mg Reinforced with Micrometer-Size Ti (by Disintegrated Melt Deposition)</i>	183
5.9.4.2	<i>MB15 Alloy Reinforced with Micrometer-Size Ti Alloy (by Powder Metallurgy Route)</i>	184
5.9.5	Addition of Molybdenum	185
5.9.5.1	<i>Mg Reinforced with Micrometer-Size Mo (by Disintegrated Melt Deposition)</i>	185
5.9.6	Addition of Aluminum	186
5.9.6.1	<i>Mg Reinforced with Micrometer-Size Al (by Powder Metallurgy—Microwave Sintering)</i>	186
5.9.6.2	<i>Mg Reinforced with 18 nm Al (by Powder Metallurgy—Conventional Sintering)</i>	187
5.9.7	Addition of Iron Wire Mesh	188
5.9.7.1	<i>Mg Reinforced with Interconnected Fe Wire Mesh (by Disintegrated Melt Deposition)</i>	188
5.9.7.2	<i>Mg Reinforced with Fe Wire Mesh and Carbon Fibers (by Disintegrated Melt Deposition)</i>	189