

---

# Table of Contents

<i>Foreword</i>	<i>iii</i>
<i>Preface</i>	<i>v</i>
<i>Acknowledgements</i>	<i>vii</i>
<b>1. INTRODUCTION</b>	<b>1</b>
1.1. Motivation	1
1.2. Advanced Materials	2
1.3. Thermodynamic Stability	2
1.4. Basis of Nonequilibrium Processing	5
1.5. Some Nonequilibrium Processing Methods	7
1.5.1. Rapid Solidification Processing	7
1.5.2. Mechanical Alloying	7
1.5.3. Plasma Processing	8
1.5.4. Vapor Deposition	8
1.5.5. Spray Forming	8
1.6. Outline of the Book	8
References	9
<b>2. HISTORICAL PERSPECTIVE</b>	<b>11</b>
2.1. Introduction	11
2.2. Historical Background	11
2.3. Development of High-Energy Ball Milling	12
2.4. Potential of Mechanical Alloying	14
2.5. Potential Resources of Mechanical Alloying Literature	14
References	17

<b>3. NOMENCLATURE</b>	<b>21</b>
3.1. Introduction	21
3.2. Mechanical Alloying	21
3.3. Mechanical Milling/Disordering	22
3.4. Reaction Milling	22
3.5. Cryomilling	23
3.6. Rod Milling	23
3.7. Mechanically Activated Annealing	24
3.8. Double Mechanical Alloying	24
3.9. Mechanically Activated Self-propagating High-temperature Synthesis	24
3.10. Oxidation–Attrition Milling–Reduction	25
3.11. Mechanochemical Processing	26
3.12. Other Methods	26
3.12.1. Repeated Cold Rolling	27
3.12.2. Multilayer Amorphization	28
3.12.3. Severe Plastic Deformation	29
3.12.4. Accumulative Roll Bonding	30
3.13. Acronyms Used in the Literature	32
References	33
<b>4. EQUIPMENT FOR MECHANICAL ALLOYING</b>	<b>35</b>
4.1. Introduction	35
4.2. Raw Materials	36
4.3. Types of Mills	37
4.3.1. Spex Shaker Mills	37
4.3.2. Planetary Ball Mills	39
4.3.3. Attritor Mills	41
4.3.4. Commercial Mills	44
4.3.5. New Designs	47
4.4. Selection of Grinding Medium	55
References	57
<b>5. PROCESS VARIABLES IN MILLING</b>	<b>59</b>
5.1. Introduction	59
5.2. Type of Mill	60
5.3. Milling Container	60
5.4. Milling Energy/Speed	61
5.5. Milling Time	64
5.6. Grinding Medium	64
5.7. Ball-to-Powder Weight Ratio	66
5.8. Extent of Filling the Vial	68
5.9. Milling Atmosphere	69
5.10. Process Control Agents	70
5.10.1. Nature of PCAs	70
5.10.2. Quantity of PCA	72

5.10.3. Constitution of the Milled Powder	74
5.10.4. Choice of PCA	75
5.11. Temperature of Milling	76
References	78
<b>6. MECHANISM OF ALLOYING</b>	<b>83</b>
6.1. Introduction	83
6.2. Ball-Powder-Ball Collisions	83
6.3. Different Stages of Processing	84
6.3.1. Early Stage of Processing	85
6.3.2. Intermediate Stage of Processing	85
6.3.3. Final Stage of Processing	87
6.4. Evolution of Particle Size	87
6.5. Ductile-Ductile Components	89
6.6. Ductile-Brittle Components	91
6.7. Brittle-Brittle Components	92
References	94
<b>7. CHARACTERIZATION OF POWDERS</b>	<b>95</b>
7.1. Introduction	95
7.2. Size and Shape	96
7.3. Surface Area	99
7.4. Phase Constitution	102
7.4.1. Crystalline Phases	102
7.4.2. Quasi-crystalline Phases	104
7.4.3. Amorphous Phases	105
7.5. Microstructural Features	107
7.6. Crystallite Size and Lattice Strain	110
7.7. Transformation Behavior	113
7.8. Grain Growth Studies	117
References	118
<b>8. TEMPERATURE RISE DURING MILLING</b>	<b>121</b>
8.1. Introduction	121
8.2. Types of Temperature Effects	122
8.3. Methods to Evaluate Temperature Rise	123
8.3.1. Methodology Behind the Theoretical Models	123
8.3.2. Theoretical Models	124
8.3.3. Observations Based on Microstructural/Phase Transformations	127
8.3.4. Experimental Observations	128
8.4. Temperature of the Balls	133
8.5. Methods to Minimize Temperature Rise	135
References	136

<b>9. SOLID SOLUBILITY EXTENSIONS</b>	<b>139</b>
9.1. Introduction	139
9.2. Hume-Rothery Rules for Solid Solution Formation	139
9.3. Formation of Supersaturated Solid Solutions	140
9.4. Measurement of Solid Solubility Limits	142
9.5. Difficulties in Solid Solubility Determination	145
9.6. Effect of Process Variables	156
9.6.1. Milling Temperature	156
9.6.2. Process Control Agent	158
9.6.3. Starting Composition of the Powder Blend	159
9.7. Mechanisms of Solid Solubility Extension	160
9.8. Solid Solubility Plots	164
9.9. Comparison between Mechanical Alloying and Rapid Solidification Processing	169
References	173
<b>10. SYNTHESIS OF INTERMETALLICS</b>	<b>183</b>
10.1. Introduction	183
10.2. Quasi-crystalline Phases	185
10.2.1. General Features	187
10.2.2. Effect of Process Variables	189
10.3. Crystalline Intermediate Phases	190
10.3.1. Metastable Crystalline Intermediate Phases	191
10.3.2. High-Pressure Phases	193
10.3.3. Equilibrium Crystalline Phases	203
10.4. Role of Hydrogen as a Temporary Alloying Element	207
10.5. Combustion Reactions during MA	209
10.6. Cyclic Phase Transformations	212
10.7. Formation of Ordered Intermetallics	216
10.8. Transformation Behavior of Metastable Intermetallic Phases	217
10.9. Refractory Compounds	220
References	227
<b>11. DISORDERING OF INTERMETALLICS</b>	<b>243</b>
11.1. Introduction	243
11.2. Methodology	244
11.3. Types of Defects Generated during Disordering and Thermodynamic Stability	245
11.3.1. Antisite Disorder	246
11.3.2. Triple-Defect Disorder	247
11.3.3. Quadruple-Defect Disorder	248
11.3.4. Redistribution of Interstitials	249
11.4. Theoretical Background	251
11.5. Phase Selection	259

11.6. Reordering Kinetics	263
References	264
<b>12. SOLID-STATE AMORPHIZATION</b>	<b>269</b>
12.1. Introduction	269
12.2. Amorphous Phases by MA/MM	270
12.3. Difference between Amorphous Phase Formation by MA and MM	271
12.4. Effect of Process Variables	291
12.4.1. Milling Energy	292
12.4.2. Milling Temperature	293
12.4.3. Powder Contamination	294
12.5. Thermodynamics and Kinetics of Amorphous Phase Formation	295
12.6. Mechanisms and Models for Amorphization	298
12.7. Crystallization Behavior of Amorphous Alloys	304
12.8. Mechanical Crystallization	306
12.9. Bulk Amorphous Alloys	307
12.10. Theoretical Predictions of Amorphous-Phase-Forming Range	312
12.11. Comparison between MA and RSP	315
References	320
<b>13. NANOSTRUCTURED MATERIALS</b>	<b>333</b>
13.1. Introduction	333
13.2. Classification and Characteristics of Nanostructured Materials	333
13.3. Synthesis of Nanostructured Materials	335
13.4. Mechanism of Formation of Nanostructures	337
13.5. Minimal Grain Size	338
13.5.1. Correlation with Material Properties	340
13.5.2. Process Variables	342
13.5.3. Theoretical Estimates	346
13.6. Nanocomposites	346
13.7. Properties of Nanocrystalline Materials	349
13.7.1. Hardness and Strength	349
13.7.2. Ductility	352
13.7.3. Enhanced Sinterability	353
13.7.4. Thermal Stability	353
References	354
<b>14. MECHANOCHEMICAL PROCESSING</b>	<b>359</b>
14.1. Introduction	359
14.2. Thermodynamic Aspects	360

14.3.	Process Parameters	369
14.3.1.	Milling Temperature	369
14.3.2.	Ball-to-Powder Weight Ratio	370
14.3.3.	Process Control Agent	371
14.3.4.	Relative Proportion of the Reactants	371
14.3.5.	Grinding Ball Diameter	372
14.4.	Phase Formation	372
14.5.	Combustion Reaction	374
14.6.	Reaction Mechanisms	375
14.6.1.	Thermal Theories	375
14.6.2.	Reactions Induced by Shear	376
14.6.3.	Theory of Surface Active States	376
14.7.	Mechanosynthesis of Ceramics and Nanocomposites	377
	References	379
<b>15.</b>	<b>POWDER CONTAMINATION</b>	<b>385</b>
15.1.	Introduction	385
15.2.	Sources of Contamination	386
15.2.1.	Starting Powders	387
15.2.2.	Milling Atmosphere	392
15.2.3.	Milling Equipment	393
15.3.	Elimination/Minimization of Contamination	395
15.3.1.	Milling Equipment	396
15.3.2.	Milling Atmosphere	398
15.3.3.	Process Control Agent	400
	References	402
<b>16.</b>	<b>MODELING STUDIES AND MILLING MAPS</b>	<b>405</b>
16.1.	Introduction	405
16.2.	Process Variables	405
16.3.	Early Modeling Attempts	406
16.4.	Types of Modeling	407
16.4.1.	Local Modeling	407
16.4.2.	Global Modeling	411
16.5.	Milling Maps	413
	References	416
<b>17.</b>	<b>APPLICATIONS</b>	<b>419</b>
17.1.	Introduction	419
17.2.	Oxide Dispersion Strengthened Materials	420
17.2.1.	ODS Nickel-Based Alloys	421
17.2.2.	ODS Iron-Based Alloys	424
17.2.3.	ODS Aluminum-Based Alloys	425

17.3.	Magnesium-Based Alloys	429
17.3.1.	Supercorrodng Alloys	429
17.3.2.	Hydrogen Storage Materials	429
17.4.	Other Applications	434
17.4.1.	Spray Coatings	434
17.4.2.	Thermoelectric Power Generator Materials	435
17.4.3.	Waste Utilization	436
17.4.4.	Metal Extraction	438
17.4.5.	Processing of Polymers	439
17.4.6.	Room Temperature Solders	441
17.4.7.	Biomaterials	441
17.4.8.	Bearings	442
17.4.9.	Miscellaneous Applications	443
17.5.	Concluding Remarks	443
	References	444
<b>18.</b>	<b>SAFETY HAZARDS</b>	<b>447</b>
18.1.	Introduction	447
18.2.	Hazards Related to Mechanical Alloying Processes	448
18.2.1.	Heat Evolution	448
18.2.2.	Gas Evolution	449
18.2.3.	Explosions	449
18.3.	Handling of Mechanically Alloyed Powders	449
18.4.	Accident Avoidance	450
	References	451
<b>19.</b>	<b>CONCLUDING REMARKS</b>	<b>453</b>
<i>Index</i>		457