

Table of Contents

Foreword	xiii
Preface	xv
Chapter 1. Some General Points about SMAs	1
1.1. Introduction	1
1.2. Why are SMAs of interest for industry?	2
1.3. Crystallographic theory of martensitic transformation	5
1.4. Content of this book	8
1.4.1. State of the art in the domain and main publications	8
1.4.2. Content of this book	8
Chapter 2. The World of Shape-memory Alloys	11
2.1. Introduction and general points	11
2.2. Basic metallurgy of SMAs, by Michel Morin	12
2.2.1. Copper-based shape-memory alloys	12
2.2.2. Cu-Zn-Al	14
2.2.3. Cu-Al-Ni	16
2.2.4. Cu-Al-Be	18
2.2.5. The phenomena of aging, stabilization and fatigue	19
2.2.6. Methods for copper-based SMA elaboration	21
2.2.7. Ti-Ni-based alloys	21
2.2.8. Ti-Ni alloy	22
2.2.9. Ti-Ni-X alloys	23
2.2.10. Elaboration	24
2.2.11. Shaping	25
2.2.12. Final heat treatments	25
2.2.13. Table comparing the physical and mechanical properties	26

2.2.14. Biocompatibility of SMAs	26
2.3. Measurements of phase transformation temperatures	27
2.4. Self-accommodating martensite and stress-induced martensite	28
2.5. Fatigue resistance	29
2.5.1. Causes of degradation of the properties	29
2.5.2. Fatigue of a Cu-Al-Be monocrystal	30
2.5.3. Results	30
2.6. Functional properties of SMAs	35
2.6.1. The pseudo-elastic effect	35
2.6.2. One-way shape-memory effect	37
2.6.3. Recovery stress	40
2.6.4. Double shape-memory effect: training	41
2.7. Use of NiTi for secondary batteries	42
2.8. Use of SMAs in the domain of civil engineering	42
Chapter 3. Martensitic Transformation	49
3.1. Overview of continuum mechanics	49
3.1.1. Main notations for vectors	49
3.2. Main notations for matrices	50
3.3. Additional notations and reminders	51
3.3.1. Unit matrices	51
3.3.2. Rotation matrix	51
3.3.3. Symmetric matrices	54
3.3.4. Positive definite symmetric matrices	54
3.3.5. Polar decomposition	55
3.4. Kinematic description	57
3.4.1. Strain gradient	57
3.4.2. Dilatation and strain tensors	58
3.4.3. Transformation of an element of volume or surface (see Figure 3.2)	60
3.5. Kinematic compatibility	61
3.6. Continuous theory of crystalline solids	62
3.6.1. Bravais lattices	63
3.6.2. Deformation of lattices and symmetry	64
3.6.3. Link between lattices and the continuous medium: Cauchy–Born hypothesis	65
3.6.4. Energy density in crystalline solids	66
3.7. Martensitic transformation	67
3.7.1. Introduction	67
3.7.2. Martensitic transformation: Bain matrix or transformation matrix	67
3.8. Equation governing the interface between two martensite variants M_i/M_j or the “ <i>twinning equation</i> ”	70

3.8.1. Cubic $\rightarrow$ quadratic transformation	72
3.8.2. Cubic $\rightarrow$ orthorhombic transformation	73
3.9. Origin of the microstructure	73
3.9.1. Simplified one-dimensional case	74
3.9.2. Simplified two-dimensional case	75
3.9.3. Three-dimensional case	76
3.10. Special microstructures	76
3.10.1. Austenite-martensite interface	76
3.10.2. Phenomenological theory of martensite	77
3.10.3. Crystallographic theory of martensite	80
3.11. From the scale of the crystalline lattice to the mesoscopic and then the macroscopic scale	84
3.11.1. Approach at the level of the crystalline lattice	85
3.11.2. Microscopic approach	86
3.11.3. Mesoscopic approach	86
3.11.4. Macroscopic approach	88
3.12. Linear geometric theory	88
3.12.1. Linearized kinematics	89
3.12.2. Linear geometric theory for phase transformation	91
3.12.3. Some microstructures and comparison	92
3.13. Chapter conclusion	95

Chapter 4. Thermodynamic Framework for the Modeling of Solid Materials

4.1. Introduction	97
4.2. Conservation laws	98
4.2.1. Concept of a material system	98
4.2.2. Concept of a particulate derivative	99
4.2.3. Mass balance	100
4.2.4. Motion balance equation	101
4.2.5. Energy balance: first law of thermodynamics	102
4.2.6. Variation of entropy: second law of thermodynamics	103
4.3. Constitutive laws	103
4.3.1. Clausius-Duhem inequality	104

Chapter 5. Use of the “CTM” to Model SMAs

5.1. Introduction	109
5.2. Process of reorientation of the martensite variants in a monocrystal	109
5.2.1. Internal variable model of the thermomechanical behavior of an SMA monocrystal	111
5.2.2. Experimental procedure and results obtained	113
5.2.3. Modeling of the experiments	114
5.2.4. Conclusion	118

5.3. Process of creation of martensite variants in a monocrystal:	
pseudoelastic behavior	118
5.3.1. Modeling the pseudoelastic behavior of the monocrystal	118
5.3.2. Traction curves	120
5.4. Prediction of the surfaces for the austenite $\rightarrow$ martensite	
phase transformation	122
5.4.1. Case of a monocrystal	122
5.4.2. Case of a polycrystal	124
Chapter 6. Phenomenological and Statistical Approaches for SMAs	129
6.1. Introduction	129
6.2. Preisach models	130
6.3. First-order phase transitions and Falk's model	132
6.3.1. Falk's model	132
6.3.2. Extension of Falk's model	136
6.3.3. Description of hysteresis loops	137
6.3.4. Phase domains with moving boundaries	138
6.3.5. Properties of the model and validation	141
6.4. Constitutive framework of the homogenized energy model	142
6.4.1. One-dimensional mesoscopic model	144
6.4.2. Thermal change	148
6.4.3. Macroscopic model	149
6.4.4. Performance of the model and material characterization	150
6.5. Conclusion	154
Chapter 7. Macroscopic Models with Internal Variables	157
7.1. Introduction	157
7.2. R_L model	159
7.2.1. Reversible R model	159
7.2.2. R_L model with a hysteresis loop	162
7.2.3. Extension to reversible phase transformation:	
austenite $\Rightarrow R$ phase for NiTi	166
7.2.4. Multiaxial isothermal behavior	168
7.3. Anisothermal expansion	173
7.3.1. Kinetics of phase transformation or reorientation	176
7.3.2. Criticism of the R_L approach	181
7.4. Internal variable model inspired by micromechanics	181
7.4.1. Introduction	181
7.4.2. Chemisky <i>et al.</i> 's model	181
7.4.3. Kelly and Bhattacharya's model	195
7.4.4. Internal variable model taking account of initiation, reorientation and saturation	198
7.4.5. Certain constraints on simulation and modeling	204

7.4.6. Certain ingredients of the model	206
7.4.7. Traction and compression for an isotropic material	213
7.4.8. Pure shearing of an isotropic material	214
7.4.9. Examination of the parameters for a uniaxial extension combined with shearing	215
7.4.10. Digital implantation	220
7.5. Elastohysteresis model: formalism and digital implantation	223
7.5.1. Experimentally-observed behaviors for shearing and traction/compression	223
7.5.2. Elasto-hysteresis model	223
7.5.3. Illustrations	229
7.6. Conclusion	233
Chapter 8. Design of SMA Elements: Case Studies	235
8.1. Introduction	235
8.2. "Strength of materials"-type calculations for beams subject to flexion or torsion	235
8.2.1. Beam with a rectangular cross-section, subject to pure flexion: theoretical study	235
8.2.2. Experimental and theoretical validation	241
8.2.3. Solving pure torsion problem: relation between the twisting torque C and the unitary angle of torsion α	242
8.3. Elements of calculations for SMA actuators	245
8.3.1. Stress/position diagram: temperature parameterization	245
8.3.2. Work provided depending on the nature of the loading	248
8.3.3. Torsion of a cylindrical wire	248
8.3.4. Flexion of a beam	248
8.3.5. Comparison of the different modes of loading	249
8.3.6. A few remarks about the duration of heating and cooling of SMAs	250
8.4. Case studies	251
8.4.1. Study of the flexion of a prismatic bar subjected to a point force	251
8.4.2. Slender tube subject to twisting torques	252
8.4.3. Study of a "parallel" hybrid structure	254
8.4.4. Study of a "series" hybrid structure	256
8.4.5. Design of an application: breakage of a mechanical link	257
Chapter 9. Behavior of Magnetic SMAs	261
9.1. Introduction	261
9.2. Some models of the thermo-magneto-mechanical behavior of MSMAs	262
9.2.1. O'Handley and Murray <i>et al.</i> 's model	262

9.2.2. Micromagnetism	263
9.2.3. Likhachev and Ullakko's model	263
9.2.4. Original approaches	263
9.2.5. Overlaps between these approaches	264
9.3. Crystallography of Ni-Mn-Ga	265
9.3.1. The different phases and variants	265
9.3.2. Rearrangement and transformation	266
9.3.3. Calculations of microstructures	267
9.4. Model of the magneto-thermo-mechanical behavior of a monocrystal of magnetic shape-memory alloy	270
9.4.1. Expression of the Gibbs free energy associated with magneto-thermo-mechanical loading	271
9.4.2. Choice of the representative elementary volume	271
9.4.3. Expression of chemical energy	273
9.4.4. Expression of thermal energy	274
9.4.5. Expression of mechanical energy	274
9.4.6. Expression of magnetic energy	275
9.4.7. General expression of the free energy	278
9.4.8. Clausius-Duhem inequality	279
9.4.9. Kinetics of phase transformation or reorientation	281
9.4.10. Heat balance equation	284
9.4.11. Identification of the parameters	285
9.4.12. Application: creation of a "push/pull" actuator	292
9.5. Conclusion	293

Chapter 10. Fracture Mechanics of SMAs 295

10.1. Introduction	295
10.2. The elastic stress field around a crack tip	296
10.2.1. Basic modes of fracture and stress intensity factors	296
10.2.2. Complex potential method for plane elasticity (the Kolosoov-Muskhelishvili formulae)	297
10.2.3. Westergaard stress functions method	301
10.2.4. Solutions by the Westergaard function method	304
10.3. Prediction of the phase transformation surfaces around the crack tip (no curvature at the crack tip)	311
10.3.1. Mode I	314
10.3.2. Mode II	314
10.3.3. Mode III	317
10.3.4. Mixed Mode I + II: analytical prediction of the transformation surfaces	318
10.4. Prediction of the phase transformation surfaces around the crack tip (curvature ρ at the crack tip)	322

10.4.1. Applications	324
10.5. Some experimental results about fracture of SMAs	325
10.6. Problem of delamination between a SMA and an elastic solid	329
Chapter 11. General Conclusion	337
11.1. Resolved problems	337
11.2. Unresolved problems	338
11.3. Suggestions for future directions	339
Appendix 1. Intrinsic Properties of Rotation Matrices (see Chapter 3) . . .	341
A1.1. Characterization of rotations	342
Appendix 2. “Twinning Equation” Demonstration (see Chapter 3)	345
A2.1. Question	345
A2.2. Solution	345
Appendix 3. Calculation of the Parameters a, n and Q from the “Twinning ” Equation (see Chapter 3)	349
A3.1. Problem	349
A3.2. Statement	349
A3.3. Solution	350
A3.3.1. Case 1	353
A3.3.2. Case 2	353
A3.3.3. Case 3	353
A3.3.4. Case 4	354
Appendix 4. “Twinned” Austenite/Martensite Equation (see Chapter 3) . .	355
A4.1. Proposition 1	355
A4.2. Proposition 2	355
A4.3. Theorem	356
Bibliography	359
Index	377