Contents

Preface v
Nomenclature xiii
Glossary xv
Abbreviations xvii

Part I Surface Roughness and Hierarchical Friction Mechanisms

1 Introduction 3
1.1 Surfaces and Surface Free Energy 3
1.2 Mesoscale 5
1.3 Hierarchy 7
1.4 Dissipation 7
1.5 Tribology 9
1.6 Biomimetics: From Engineering to Biology and Back 11

2 Rough Surface Topography 13
2.1 Rough Surface Characterization 13
2.2 Statistical Analysis of Random Surface Roughness 17
2.3 Fractal Surface Roughness 20
2.4 Contact of Rough Solid Surfaces 23
2.5 Surface Modification 25
2.5.1 Surface Texturing 25
2.5.2 Layer Deposition 25
2.6 Summary 26

3 Mechanisms of Dry Friction, Their Scaling and Linear Properties . . . 27
3.1 Approaches to the Multiscale Nature of Friction 28
3.2 Mechanisms of Dry Friction 31
3.2.1 Adhesive Friction 31

3.2.2 Deformation of Asperities 38
3.2.3 Plastic Yield 39
3.2.4 Fracture 39
3.2.5 Ratchet and Cobblestone Mechanisms 39
3.2.6 "Third Body" Mechanism 40
3.2.7 Discussion 40
3.3 Friction as a Linear Phenomenon 40
3.3.1 Friction, Controlled by Real Area of Contact 41
3.3.2 Friction Controlled by Average Surface Slope 43
3.3.3 Other Explanations of the Linearity of Friction 44
3.3.4 Linearity and the "Small Parameter" 45
3.4 Summary 45

4 Friction as a Nonlinear Hierarchical Phenomenon 47
4.1 Nonlinear Effects in Dry Friction 47
4.1.1 Nonlinearity of the Amontons–Coulomb Rule 47
4.1.2 Dynamic Instabilities Associated with the Nonlinearity 48
4.1.3 Velocity-Dependence and Dynamic Friction 49
4.1.4 Interdependence of the Load-, Size-, and Velocity-Dependence of the Coefficient of Friction 50
4.1.5 Stick–Slip Motion 51
4.1.6 Self-Organized Criticality 52
4.2 Nonlinearity and Hierarchy 53
4.3 Heterogeneity, Hierarchy and Energy Dissipation 55
4.3.1 Ideal vs. Real Contact Situations 55
4.3.2 Measure of Inhomogeneity and Dissipation at Various Hierarchy Levels 55
4.3.3 Order-Parameter and Mesoscopic Functional 59
4.3.4 Kinetics of the Atomic-Scale Friction 59
4.4 Mapping of Friction at Various Hierarchy Levels 61
4.5 Summary 62

Part II Solid–Liquid Friction and Superhydrophobicity

5 Solid–Liquid Interaction and Capillary Effects 65
5.1 Three Phase States of Matter 65
5.2 Phase Equilibrium and Stability 67
5.3 Water Phase Diagram at the Nanoscale 69
5.4 Surface Free Energy and the Laplace Equation 72
5.5 Contact Angle and the Young Equation 73
5.6 Kelvin's Equation 76
5.7 Capillary Effects and Stability Issues 77
5.8 Summary 79

6 Roughness-Induced Superhydrophobicity 81
6.1 The Phenomenon of Superhydrophobicity 81
6.2 Contact Angle Analysis 85
6.3 Heterogeneous Surfaces and Wenzel and Cassie Equations 86
6.3.1 Contact Angle with a Rough and Heterogeneous Surfaces . . 86
6.3.2 The Cassie–Baxter Equation 87
6.3.3 Limitations of the Wenzel and Cassie Equations 90
6.3.4 Range of Applicability of the Wenzel and Cassie Equations . 92
6.4 Calculation of the Contact Angle for Selected Surfaces 96
6.4.1 Two-Dimensional Periodic Profiles 96
6.4.2 Three-Dimensional Surfaces 100
6.4.3 Surface Optimization for Maximum Contact Angle 105
6.5 Contact Angle Hysteresis 107
6.5.1 Origin of the Contact Angle Hysteresis 107
6.5.2 Pinning of the Triple Line 109
6.5.3 Contact Angle Hysteresis and the Adhesion Hysteresis 110
6.6 Summary 112

7 Stability of the Composite Interface, Roughness and Meniscus Force . 115
7.1 Destabilization of the Composite Interface 115
7.1.1 Destabilization Due to Capillary and Gravitational Waves . . 116
7.1.2 Probabilistic Model 121
7.1.3 Analysis of Rough Profiles 122
7.1.4 Effect of Droplet Weight 123
7.2 Contact Angle with Three-Dimensional Solid Harmonic Surface . . . 126
7.2.1 Three-Dimensional Harmonic Rough Surface 126
7.2.2 Calculations of the Contact Areas 128
7.2.3 Metastable States 129
7.2.4 Overall Contact Angle 130
7.2.5 Discussion of Results 131
7.2.6 The Similarity of Bubbles and Droplets 133
7.3 Capillary Adhesion Force Due to the Meniscus 134
7.3.1 Sphere in Contact with a Smooth Surface 134
7.3.2 Multiple-Asperity Contact 136
7.4 Roughness Optimization 137
7.5 Effect of the Hierarchical Roughness 141
7.5.1 Hierarchical Roughness 141
7.5.2 Stability of a Composite Interface and Hierarchical Roughness 142
7.5.3 Hierarchical Roughness 145
7.5.4 Results and Discussion 148
7.6 Summary 151

8 Cassie–Wenzel Wetting Regime Transition 153
8.1 The Cassie–Wenzel Transition and the Contact Angle Hysteresis . . . 153

8.2 Experimental Study of the Cassie–Wenzel Transition 157
8.3 Wetting as a Multiscale Phenomenon 163
8.4 Investigation of Wetting as a Phase Transition 165
8.5 Reversible Superhydrophobicity 166
8.6 Summary 166

9 Underwater Superhydrophobicity and Dynamic Effects 169
9.1 Superhydrophobicity for the Liquid Flow 169
9.2 Nanobubbles and Hydrophobic Interaction 171
9.3 Bouncing Droplets 172
9.4 A Droplet on a Hot Surface: the Leidenfrost Effect 175
9.5 A Droplet on an Inclined Surface 176
9.6 Summary 177

Part III Biological and Biomimetic Surfaces

10 Lotus-Effect and Water-Repellent Surfaces in Nature 181
10.1 Water-Repellent Plants 181
10.2 Characterization of Hydrophobic and Hydrophilic Leaf Surfaces . . . 184
10.2.1 Experimental Techniques 184
10.2.2 Hydrophobic and Hydrophilic Leaves 185
10.2.3 Contact Angle Measurements 186
10.2.4 Surface Characterization Using an Optical Profiler 187
10.2.5 Leaf Characterization with an AFM 190
10.2.6 Adhesion Force and Friction 192
10.2.7 Role of the Hierarchy 196
10.3 Other Biological Superhydrophobic Surfaces 197
10.4 Summary 197

11 Artificial (Biomimetic) Superhydrophobic Surfaces 199
11.1 How to Make a Superhydrophobic Surface 201
11.1.1 Roughening to Create One-Level Structure 202
11.1.2 Coating to Create One-Level Hydrophobic Structures 204
11.1.3 Methods to Create Two-Level (Hierarchical) Superhydrophobic Structures 205
11.2 Experimental Techniques 206
11.2.1 Contact Angle, Surface Roughness, and Adhesion 206
11.2.2 Measurement of Droplet Evaporation 207
11.2.3 Measurement of Contact Angle Using ESEM 207
11.3 Wetting of Micro- and Nanopatterned Surfaces 208
11.3.1 Micro- and Nanopatterned Polymers 208
11.3.2 Micropatterned Si Surfaces 211
11.4 Self-cleaning 227
11.5 Commercially Available Lotus-Effect Products 228
11.6 Summary 229

12 Gecko-Effect and Smart Adhesion 231
12.1 Gecko 231
12.2 Hierarchical Structure of the Attachment Pads 233
12.3 Model of Hierarchical Attachment Pads 236
12.4 Biomimetic Fibrillar Structures 237
12.5 Self-cleaning 239
12.6 Biomimetic Tape Made of Artificial Gecko Skin 240
12.7 Summary 241

13 Other Biomimetic Surfaces 243
13.1 Hierarchical Organization in Biomaterials 243
13.2 Moth-Eye-Effect 244
13.3 Shark Skin 246
13.4 Darkling Beetle 246
13.5 Water Strider 247
13.6 Spider Web 247
13.7 Other Biomimetic Examples 248
13.8 Summary 249

14 Outlook 251

References 255

Index 271