Contents

Preface  XI
Glossary  XVII

1  Bioceramics – A Historical Perspective  1
  1.1  Alumina  1
  1.2  Zirconia  3
  1.3  Calcium Phosphates  4
  References  6

2  Socio-Economic Aspects and Scope of Bioceramic Materials and Biomedical Implants  11
  2.1  Types of Biomaterial  11
  2.2  The Growing Global and Regional Markets for Biomedical Implants  14
    2.2.1  A Worldwide Need for Implants  14
    2.2.2  Market Projections and Forecasts for Biomaterials and Biomedical Implants  17
      2.2.2.1  Biomaterials  17
      2.2.2.2  Large-Joint Reconstruction Implants (Hip and Knee)  19
      2.2.2.3  Small Joints and Extremities Implants  20
      2.2.2.4  Spinal Implants  21
      2.2.2.5  Dental Implants  21
    2.3  Role of Bioceramic Coatings in Arthroplasty  22
    2.4  Ceramic Femoral Ball Heads  26
      2.4.1  Mechanical and Functional Properties  26
      2.4.2  Manufacturing of Ceramic Femoral Ball Heads  27
      2.4.3  Discolouration of Zirconia by Ionising Radiation  30
    References  35

3  Fundamentals of Interaction of Bioceramics and Living Matter  41
  3.1  Principle of Biocompatibility  41
  3.2  Hierarchical Structure of Bone and Teeth  44
    3.2.1  Bone Structure  44
5.2.4 Electrochemical Deposition (ECD) 146
5.2.4.1 Electrochemical Reactions 147
5.2.4.2 Acid–Base Reactions 147
5.2.4.3 Precipitation Reactions 148
5.2.5 Electrophoretic Deposition (EPD) 152
5.2.5.1 General Aspects 152
5.2.5.2 Electrophoretic Deposition of Calcium Phosphate Coatings 154
5.2.6 Thermal Substrate Deposition (Hydroprocessing) 158
5.2.7 Hydrothermal Coating Deposition 162
5.2.8 Electron- and Ion Beam-Assisted Deposition (EBAD, IBAD) 163
5.2.9 Radio Frequency (r.f.) Magnetron Sputtering 167
5.3 Thermal Deposition Methods 172
5.3.1 Atmospheric Plasma Spraying (APS) 173
5.3.1.1 The Physics Behind the Process 173
5.3.1.2 Micro-Plasma Spraying (MPS) and Low Energy Plasma Spraying (LEPS) 179
5.3.2 Low-Pressure (Vacuum) Plasma Spraying (LPPS, VPS) 182
5.3.3 Suspension Plasma Spraying (SPS) 185
5.3.3.1 Hydroxyapatite Coatings 188
5.3.3.2 Titanium Oxide Coatings 190
5.3.3.3 Bioglass Coatings 191
5.3.3.4 Other Types of Coating 192
5.3.4 High Velocity Suspension Flame Spraying (HVSFS) 193
5.3.4.1 Hydroxyapatite Coatings 194
5.3.4.2 Titanium Oxide Coatings 196
5.3.4.3 Bioglass Coatings 197
5.3.4.4 Other Coatings 199
5.3.5 Solution Precursor Plasma Spraying (SPPS) 200
5.3.6 Cold Gas Dynamic Spraying (CGDS) 201
5.3.6.1 Fundamentals 201
5.3.6.2 Bioceramic Coatings 204
5.3.7 Plasma Electrolytic Oxidation (PEO) 209
5.3.7.1 Magnesium Substrates 212
5.3.7.2 Titanium Substrates 214
5.3.8 Pulsed Laser Deposition (PLD) 219
5.4 Other Techniques 222
5.4.1 Flame Spraying 222
5.4.1.1 Oxygen/Acetylene Flame Spraying 222
5.4.1.2 High Velocity Oxyfuel Spraying (HVOF) 222
5.4.2 Inductively Coupled Plasma Spraying (ICPS) 224
5.4.3 Chemical Vapour Deposition (CVD) 224
5.4.4 Laser Alloying 226
5.4.5 Phase Inversion Technique 226

References 227
6  Deposition, Structure, Properties and Biological Function of Plasma-Sprayed Bioceramic Coatings  253
6.1 General Requirements and Performance Profile of Plasma-Sprayed Bioceramic Coatings 253
6.2 Structure and Biomedical Functions of Bioceramic Coatings 258
6.2.1 Hydroxyapatite Coatings 258
6.2.1.1 Microstructural and Compositional Changes During Plasma Spraying and Incubation in SBF 258
6.2.1.2 Thermal Decomposition of Hydroxyapatite During Plasma Spraying 263
6.2.1.3 Parametric Study of Thermal Decomposition of Hydroxyapatite 269
6.2.1.4 The Oxyapatite Problem 272
6.2.1.5 Biological Responses to Hydroxyapatite Coatings 275
6.2.2 Composite Coatings 278
6.2.2.1 Hydroxyapatite/Titania Composite Coatings 278
6.2.2.2 Hydroxyapatite/Zirconia Composite Coatings 278
6.2.2.3 Hydroxyapatite/Alumina/Carbon Nanotube Composite Coatings 280
6.2.3 Biphasic Hydroxyapatite/Tricalcium Phosphate Coatings 280
6.2.4 Transition Metal-Substituted Calcium Orthophosphate Coatings 281
6.2.4.1 Coating Thickness 281
6.2.4.2 Coating Porosity 282
6.2.4.3 Tensile Adhesion and Shear Strengths 283
6.3 The Role of Bond Coats 283
6.3.1 Engineering the Substrate–Coating Interface 283
6.3.2 Selected Bond Coats 285
6.3.2.1 Calcium Silicate Bond Coats 285
6.3.2.2 Titania Bond Coats 288
6.3.2.3 Zirconia Bond Coats 292
6.3.2.4 Mixed Zirconia/Titania Bond Coats 294
References 298

7  Characterisation and Testing of Bioceramic Coatings 309
7.1 Phase Composition: X-ray Diffraction 310
7.1.1 Fundamentals 310
7.1.2 X-ray Diffraction of Plasma-Sprayed Hydroxyapatite Coatings 312
7.2 Phase Composition: Vibrational (Infrared and Raman) Spectroscopy 314
7.2.1 Fundamentals 314
7.2.1.1 Infrared Spectroscopy 314
7.2.1.2 Raman Spectroscopy 315
7.2.2 Raman Microscopy of Bioceramic and Photoactive Titania Coatings 316
7.2.3 Infrared and Raman Spectra of Hydroxyapatite Coatings 318
7.2.3.1 Fourier Transform Infrared (FTIR) Spectroscopy 318
7.2.3.2 Raman spectroscopy 321
7.3 Phase Composition: Nuclear Magnetic Resonance Spectroscopy 325
7.3.1 Fundamentals 325
7.3.2 NMR Spectra of Hydroxyapatite Coatings 326
7.4 Phase Composition: Cathodoluminescence 333
7.4.1 Fundamentals 333
7.4.2 Cathodoluminescence Microscopy of Plasma-Sprayed Hydroxyapatite Coatings 334
7.5 Adhesion of Coatings to the Substrate 340
7.5.1 Fundamentals 340
7.5.1.1 Tensile Pull Test 342
7.5.1.2 Modified Peel Test 343
7.5.1.3 Scratch Testing 346
7.5.1.4 Ultrasonic Testing 349
7.5.2 Adhesion of Plasma-Sprayed Hydroxyapatite Coatings 351
7.5.2.1 Modified Peel Test According to ASTM D3167-10 351
7.5.2.2 Tensile Test 353
7.5.2.3 Scratch Test 354
7.5.2.4 Laser Shock Adhesion Test (LASAT) 356
7.6 Residual Coating Stresses 358
7.6.1 Fundamentals 358
7.6.2 X-ray Diffraction Measurements (sin^2Ψ-Technique) 361
7.6.3 Stress Determination by Curvature Measurement (Almen-Type Test) 363
7.6.4 Hole-Drilling Strain Gauge Method 365
7.6.5 Photoluminescence Piezospectroscopy 367
7.6.6 Residual Stresses in Plasma-Sprayed Hydroxyapatite Coatings 370
7.6.6.1 Stress Analysis by X-ray Diffraction 370
7.6.6.2 Stress Analysis by Curvature Measurement 374
7.6.6.3 Stress Analysis by the Hole-Drilling Strain Gauge Method 376
7.6.6.4 Stress Analysis by Raman Piezospectroscopy 377
7.7 Fundamentals of Roughness and Porosity 377
7.8 Microhardness 382
7.8.1 Fundamentals 382
7.8.2 Microhardness of Hydroxyapatite Coatings 386
7.9 Potentiodynamic Polarisation and Electrochemical Impedance Spectroscopy (EIS) 387
7.9.1 Fundamentals 387
7.9.2 Corrosion Protection of Metal Implants through Coatings 389
7.10 Biological Performance Testing of Bioceramic Coatings 392
7.10.1 Composition of Simulated Body Fluids 393
7.10.2 Interaction of Simulated Body Fluids and Coatings 394
7.10.2.1 Structure and Transformation of Amorphous Calcium Phosphate (ACP)  395
7.10.2.2 EELS and PIXE Studies  402
7.10.3 Cell Proliferation and Viability Tests  405
7.10.3.1 Alkaline Phosphatase (ALP) Activity  405
7.10.3.2 Expression of Non-collagenous Proteins  406
7.10.3.3 AlamarBlue® and MTT Assays  409
7.10.3.4 Fluorescence Staining  411
7.10.4 In vivo Testing of Bioceramic Coatings Using Animal Models  414
7.10.4.1 Rat Model  416
7.10.4.2 Rabbit Model  417
7.10.4.3 Dog Model  420
7.10.4.4 Sheep Model  423
7.10.4.5 Other Animal Models  429
References  429

8 Future Developments and Outlook  445
References  451

Appendix: Relevant Scientific Journals/Book Series with Bioceramic Content  455

Index  459