Contents

1. Introduction **13**

1.1. Thin films — an overview 13
1.2. The aim and scope of the monograph 16
1.3. Thin films deposition methods 19
1.3.1. Physical vapour deposition 19
1.3.2. Chemical vapour deposition 20
1.3.3. Thermal spray deposition 21
1.4. Failure modes in thin films 22
1.5. Thermal barrier coating system 25
1.5.1. Substrate alloy 27
1.5.2. Bond coat 28
1.5.3. Thermal barrier coatings 30
1.5.4. Degradation of APS TBC systems 33
1.5.5. Modelling of TBC systems 35
1.6. Human skin 38
1.6.1. Structure of human skin 38
1.6.2. Mechanical properties of human skin 39
1.6.3. Skin imaging 41

2. Preliminaries **45**

2.1. Fracture mechanics of interface cracks 45
2.1.1. General case $\epsilon \neq 0$ 47
2.1.2. Special case $\epsilon = 0$ 49
2.1.3. Energy release rate 50
2.2. Cohesive zone model 51
2.2.1. General formulation 52
2.2.2. Specification to a slip response 56

3. An energy model of segmentation cracking of thin films 59
3.1. Introduction . . . 59
3.2. Problem formulation . . . 60
3.3. Residual stresses . . . 63
3.4. External loading . . . 65
3.4.1. Stage I . . . 67
3.4.2. Stage II . . . 69
3.5. Energy model . . . 71
3.5.1. Failure model based on the total system energy . . . 72
3.5.2. Failure model based on the film/interface sub-system energy . . . 79
3.6. Specification of the fracture energy of a silicon oxide thin coating . . . 80
3.7. The energy model and stress redistribution models . . . 88
3.8. Conclusions . . . 90

4. Modelling of thermal barrier coatings 93
4.1. Introduction . . . 93
4.2. Through-thickness cracking cracking . . . 94
4.2.1. Experimental setup . . . 94
4.2.2. Experimental results . . . 96
4.2.3. Finite element model . . . 99
4.2.4. Mesh dependence . . . 105
4.2.5. Comparison with experimental results . . . 106
4.2.6. Effect of TBC critical energy release rate G_{I} on segmentation cracking . . . 108
4.3. Delamination . . . 109
4.3.1. The numerical model . . . 110
4.3.2. The time dependent behaviour of CMSX-4 . . . 115
4.3.3. Modelling of crack development . . . 116
4.3.4. Stress distribution without microcracks in the unit cell . . . 117
4.3.4.1. The influence of the time-dependent behaviour of CMSX-4 117
4.3.4.2. The effect of cyclic loading . . . 120
4.3.5. Crack development at the TGO/BC interface . . . 126
4.4. Conclusions . . . 131

5. Frictional delamination 135
5.1. Introduction . . . 135
5.2. Problem formulation . . . 136
5.3. Dimensional analysis . . . 140
5.4. Observations - one dimensional slip model . . . 142
5.5. Superposition of solution . . . 145
5.6. Moving boundary $\partial\Omega$ . . . 148
5.7. Approximate solution . . . 151
5.8. Results . . . 154
5.8.1. Special case: $\nu = -1$ . . . 154

5.8.2. Loading force P versus parameter l_0 156
5.8.3. Stress field 158
5.8.4. Comparison with finite element results 158
5.9. Conclusions 161

6. Characterization of thin tissues via surface-wave sensing 165
6.1. Introduction 165
6.2. Conceptual sensor setup 166
6.3. Point versus integral motion sensing 168
6.4. Forward analysis 169
6.4.1. Layered tissue model 169
6.4.2. Sensing array 170
6.4.3. Response of the substrate 170
6.4.4. Response of the fiber 172
6.4.5. Fiber-substrate interaction 174
6.4.6. Solution method 174
6.4.7. Computation of output voltages 176
6.4.8. Comparison with finite element simulations 177
6.4.9. Dominant modes of sensors' deformation 177
6.5. Back-analysis 182
6.5.1. Observations 182
6.5.2. Minimization 183
6.6. Numerical results 184
6.6.1. Effect of number of sensors 185
6.6.2. Effect of frequency sweep 185
6.6.3. Experimental noise 188
6.7. Conclusions 191

7. Summary 193

A. Green's function for a one dimensional elastic strip 199

B. Green's functions for an infinite plate loaded by an in-plane point force 201

C. Parameters used in equations (6.4) 209

Bibliography 211

Extended summary in Polish 229