

Anthony C. Fischer-Cripps

Nanoindentation

Third Edition



 Springer

Contents

1	Contact Mechanics.....	1
1.1	Introduction.....	1
1.2	Elastic Contact	1
1.3	Geometrical Similarity.....	6
1.4	Elastic–Plastic Contact.....	8
1.4.1	The Constraint Factor.....	8
1.4.2	Indentation Response of Materials.....	9
1.4.3	Elastic–Plastic Stress Distribution	10
1.4.4	Hardness Theories	11
1.5	Indentations at the Nanometre Scale.....	14
	References	17
2	Nanoindentation Testing.....	21
2.1	Nanoindentation Test Data	21
2.2	Indenter Types	21
2.3	Indentation Hardness and Modulus.....	24
2.3.1	Spherical Indenter	25
2.3.2	Vickers Indenter	26
2.3.3	Berkovich Indenter.....	27
2.3.4	Cube Corner Indenter.....	28
2.3.5	Knoop Indenter.....	28
2.4	Load–Displacement Curves	29
2.5	Experimental Techniques	32
2.5.1	Instrument Construction and Installation	33
2.5.2	Indenters	34
2.5.3	Specimen Mounting	35
2.5.4	Working Distance and Initial Penetration	35
2.5.5	Test Cycles	36
	References	37

3 Analysis of Nanoindentation Test Data	39
3.1 Analysis of Indentation Test Data	39
3.2 Analysis Methods	39
3.2.1 Cylindrical Punch Indenter	39
3.2.2 Conical Indenter—Cylindrical Punch Approximation.....	41
3.2.3 Spherical Indenter	43
3.2.4 Berkovich Indenter.....	47
3.2.5 Knoop Indenter	52
3.2.6 Effective Indenter Shape.....	55
3.2.7 Energy Methods	59
3.2.8 Dynamic Methods.....	67
3.2.9 Other Methods of Analysis	68
References	72
4 Factors Affecting Nanoindentation Test Data	77
4.1 Introduction	77
4.2 Thermal Drift.....	77
4.3 Initial Penetration Depth	78
4.4 Instrument Compliance	81
4.5 Indenter Geometry	84
4.6 Piling-Up and Sinking-In	88
4.7 Indentation Size Effect.....	91
4.8 Surface Roughness	93
4.9 Tip Rounding.....	95
4.10 The Plastic Depth	97
4.11 Residual Stresses	99
4.12 Friction and Adhesion	101
4.13 Specimen Preparation.....	102
References	103
5 Simulation of Nanoindentation Test Data	105
5.1 Introduction	105
5.2 Spherical Indenter	105
5.3 Berkovich Indenter.....	107
5.4 Conical and Power Law Indenters	108
5.5 Finite Element Analysis	111
5.6 Comparison of Simulated and Experimental Data.....	113
References	117
6 Scaling Relationships in Nanoindentation	119
6.1 Scaling Relationships in Nanoindentation	119
References	123

7 Time-dependent Nanoindentation	125
7.1 Introduction	125
7.2 Dynamic Indentation Testing	126
7.2.1 Single Frequency Dynamic Analysis	126
7.2.2 Multiple Frequency Dynamic Analysis.....	134
7.3 Creep	136
References.....	144
8 Nanoindentation of Thin Films and Small Volumes of Materials	147
8.1 Introduction	147
8.2 Testing of Thin Films	147
8.2.1 Elastic Modulus.....	148
8.2.2 Hardness.....	150
8.2.3 Film Adhesion	152
8.3 Scratch Testing.....	155
8.4 Small Volumes of Materials	158
References.....	159
9 Other Techniques in Nanoindentation	163
9.1 Introduction	163
9.2 Acoustic Emission Testing	163
9.3 Constant Strain Rate Testing.....	165
9.4 Fracture Toughness	166
9.5 High-Temperature Nanoindentation Testing.....	169
9.6 Strain-hardening Exponent	172
9.7 Impact	174
9.8 Residual Stress	174
9.9 Surface Forces.....	177
References.....	178
10 Nanoindentation Test Standards	181
10.1 Nanoindentation Test Standards.....	181
10.2 ISO 14577	181
10.2.1 ISO 14577 Part 1: Test Method.....	183
10.2.2 ISO 14577 Part 2: Verification and Calibration of Machines	191
10.2.3 ISO 14577 Part 3: Calibration of Reference Blocks	194
10.2.4 ISO 14577 Part 4: Test Method for Coatings	194
References.....	198
11 Nanoindentation Instrumentation	199
11.1 Specifications of Nanoindentation Test Instruments.....	199
11.2 Head Design	202
11.2.1 Actuator	203
11.2.2 Force Measurement.....	204
11.2.3 Depth Measurement	206

11.3	Frame Construction	208
11.4	Specimen Positioning	208
11.5	Imaging.....	210
11.6	Scratch Testing.....	210
	References.....	211
12	Applications of Nanoindentation	213
12.1	Introduction	213
12.2	Fused Silica.....	214
12.3	Titanium Dioxide Thin Film.....	215
12.4	Superhard Thin Film.....	216
12.5	Diamond-like Carbon (DLC) Thin Film	217
12.6	Creep in Polymer Film	218
12.7	Fracture and Delamination of a Silicon Oxide Film.....	220
12.8	High-temperature Testing	221
12.9	Adhesion Measurement	222
12.10	Dynamic Hardness.....	222
12.11	Repeatability Testing	223
12.12	Bone.....	224
12.13	AFM Imaging	226
12.14	Conductive Nanoindentation	226
12.15	Thermal Barrier Coating.....	227
12.16	Hardness of Diamond	227
12.17	Variation in H/E_r with Temperature	229
12.18	Impact Indentation of Wear Resistant Coatings	230
12.19	Mechanical Property Mapping	231
12.20	Other Applications	231
	References	232
13	Appendices 1–7	235
13.1	Elastic Indentation Stress Fields.....	235
13.1.1	Contact Pressure Distributions.....	235
13.1.2	Indentation Stress Fields	236
13.2	Surface Forces, Adhesion and Friction.....	238
13.2.1	Adhesion Forces in Nanoindentation	238
13.2.2	Forces in Nature	239
13.2.3	Interaction Potentials.....	239
13.2.4	Van der Waals Forces	241
13.2.5	Surface Interactions.....	241
13.2.6	Adhesion.....	243
13.2.7	Friction	247
13.3	Common Indenter Geometries.....	250
13.3.1	Berkovich Indenter.....	250
13.3.2	Vickers Indenter	251

13.3.3	Knoop Indenter	252
13.3.4	Sphero-Conical Indenter	253
13.4	Non-linear Least Squares Fitting.....	253
13.5	Properties of Materials.....	257
13.6	Frequently Asked Questions.....	258
13.7	Specifications for a Nanoindenter	269
13.7.1	Instrument Function	270
13.7.2	Basic Specifications and Construction.....	271
13.7.3	Specimen Positioning.....	272
13.7.4	Specimen Mounting	272
13.7.5	Optical Microscope and Imaging	273
13.7.6	Software	273
13.7.7	Accessories.....	274
13.7.8	Instrument Mounting and Isolation.....	274
13.7.9	Delivery, Calibration and Warranty	274
13.7.10	Instrument/Supplier Checklist.....	275
	References.....	276
	Index.....	277