TABLE OF CONTENTS

Preface & Acknowledgements xvii

I. Introduction to precision manufacturing 1

1.1 Precision Engineering 1
1.2 Precision Manufacturing 2
1.3 Competitive drivers of precision manufacturing 7
1.4 Historical developments in manufacturing 9
    1.4.1 Background 9
    1.4.2 Key Drivers 13
    1.4.3 Historical Examples 16
1.5 Organization of this book 33

II. Machine design for precision manufacturing 37

2.1 Background on machine design for manufacturing 37
2.2 Philosophy of precision machine design 39
2.3 Sources of error - overview 41

III. Principles of measurement 49

3.1 Definition of terms – accuracy, repeatibility, and Resolution 49
    3.1.1 Accuracy 49
    3.1.2 Repeatability (or precision) 53
    3.1.3 Resolution 54
    3.1.4 Probabilistic measure of accuracy 55
3.2 Metrology and measurement 57

3.3 Abbé's principle 64
3.4 Metrology techniques 67
    3.4.1 Measurement of dimension and angle 67
    3.4.2 Measurement of form 73
        3.4.2.1 Straightness 73
        3.4.2.2 Flatness 84
        3.4.2.3 Roundness 88
        3.4.2.4 Other form errors 99
    3.4.3 Measurement of surface roughness 99
    3.4.4 Kinematic precision 110
3.5 Subsurface damage 112

IV. Mechanical errors 121

4.1 Introduction 121
4.2 Errors due to machine elements (excluding bearings) 123
4.3 Kinematic design 128
    4.3.1 Connectivity 128
    4.3.2 Kinematic elements 129
    4.3.3 Contact and complex support 133
    4.3.4 Summary of kinematic design 142
4.4 Structural compliance 143
    4.4.1 Microscale compliance 143
    4.4.2 Macroscale compliance 145
4.5 Bearings and spindles 153
    4.5.1 Bearings 153
    4.5.2 Aerostatic bearings and spindles 163

V. Thermal errors 167

5.1 Background on the thermal error problem 167
5.2 Thermal effects in precision engineering 171
5.3 Determining the effect of temperature other than 20°C 180
    5.3.1 Free and constrained bodies 181
    5.3.2 Effect of spatial temperature gradients 184
    5.3.3 Effect of temperature transients: soak-out time and sinusoidal response 187

5.4 Conductive, convective, and radiative heat transfer parameters 193
5.5 Specific heat sources and examples of thermal problems 196
5.6 Environmental control of precision machinery 202
    5.6.1 Machine enclosures 203
    5.6.2 Factory and room enclosures 204
    5.6.3 Machine treatment without enclosures 206
5.7 Thermal effects and metrology 208
5.8 Observations 215

VI. Error mapping and error budgets 217

6.1 Introduction 217
6.2 Error mapping 218
6.3 Error budget 232
    6.3.1 Definition of error budget 232
    6.3.2 Error budget flow chart 233
    6.3.3 Combinational rules for errors 234

VII. Error due to compliance and vibration 239

7.1 Introduction 239
7.2 Excitations in machine tools 243
7.3 Weight deformation 246
7.4 Cutting force deformation 249
    7.4.1 Type A deformation: Deformation due to the variation of the cutting force 250
        7.4.1.1 Introduction and background 250
        7.4.1.2 Examples for single edge cutting 254
        7.4.1.3 Machine stiffness and directional orientation 256
    7.4.2 Type B deformation: Deformation due to the variation of the stiffness along the tool path 263
    7.4.3 Comparison of the errors from deformation types A and B 267
7.5 Forced vibrations 272
7.6 Self-excited vibrations (chatter) 273
    7.6.1 Introduction 273
    7.6.2 Basic stability; effect of structural dynamics 278

7.6.3 Variation of spindle speed and stability lobes 288
7.7 Advanced analysis 292

VIII. Sensors for precision manufacturing 295

8.1 Introduction 295
8.1.1 The relevance of precision manufacturing and the need for in-process monitoring and control 295
8.1.2 Requirements for sensor technology for precision manufacturing 297
8.2 Overview of sensors in manufacturing 300
8.2.1 Introduction 300
8.2.2 Sensor systems for process monitoring 303
8.3 New developments in signal and information processing for tool condition monitoring 308
8.3.1 Introduction 308
8.3.2 Intelligent sensors 311
8.3.3 Implementation strategies 314
8.3.4 Multisensor approaches 316
8.3.5 Sensors for high speed machining 317
8.4 Acoustic emission in manufacturing 320
8.4.1 Background 320
8.4.2 Acoustic emission sources-diagnostics 322
8.4.3 Acoustic emission sources-process monitoring 323
8.4.4 Acoustic emission in machining 325
8.5 Signal processing, feature extraction and sensor fusion 334
8.5.1 Introduction 334
8.5.2 Intelligent sensor defined 337
8.5.3 Sensor fusion defined 338
8.5.4 Fusion methodologies 339
8.5.5 Neural networks 341
8.6 Applications of signal processing and sensor fusion 349
8.6.1 Introduction 349
8.6.2 Tool wear detection using time series analysis of acoustic emission 350

8.6.2.1 Time series analysis 351
8.6.2.2 Experimental evaluation 355
8.7 Sensor integration using neural networks for intelligent tool condition monitoring 358
8.7.1 Use of multiple sensors 360
8.7.2 Experimental evaluation 363
8.8. The need for engineering models to design and predict the performance of in-process sensors 369
8.9 Basic sensor classification and new sensing technologies 372
8.9.1 Introduction 372
8.9.2 Basic sensor types 377
8.9.2.1 Mechanical sensors 377
8.9.2.2 Thermal sensors 380
8.9.2.3 Electrical sensors 382
8.9.2.4 Magnetic sensors 382
8.9.2.5 Radiant sensors 383
8.9.2.6 Chemical sensors 383
8.10 Applications of sensors in precision manufacturing 384
8.10.1 AE-based monitoring of grinding wheel dressing 384
8.10.1.1 Fast AE RMS analysis for wheel condition monitoring 385
8.10.1.2 Grinding wheel topographical mapping 387
8.10.1.3 Wheel wear mechanism 389
8.10.1.4 AE-based monitoring of face milling 390
8.10.2 AE-based monitoring of chemical mechanical planarization 393
8.10.2.1 Monitoring of abrasive process parameters 395
8.10.2.2 Precision scribing of CMP-treated wafers 398
8.10.2.3 AE-based endpoint detection for CMP 401
8.10.2.4 AE monitoring of surface chemical reactions for copper CMP 403

        8.10.2.5 AE characteristics of oxidation and dissolution in copper CMP 411
        8.10.2.6 Monitoring of precision scribing 416
        8.10.2.7 Monitoring of ultraprecision Turning of Single crystal copper 418
        8.10.2.8 Monitoring of ultraprecision turning of polycrystalline copper 421
8.11 Summary 422

IX. Process planning for precision manufacturing 425

9.1 Manufacturing system characteristics 425
9.2 Process planning basics 435
9.3 Process capability 438
    9.3.1 Background 438
    9.3.2 Process capability defined 440
9.4 C_p as a planning metric 444
9.5 Legacy-system integration for precision manufacturing 451
9.6 Future integration for precision manufacturing process planning 452

X. Precision machining processes 455

10.1 Introduction 455
10.2 Influence of machining parameters, work material, and Tool geometry 462
    10.2.1 Influence of uncut chip thickness 462
    10.2.2 Machining brittle materials 465
    10.2.3 Effects of work material crystallography/ directionality 472
10.3 Process operating conditions 478
10.4 Precision mfg. processes-diamond turning/milling 482
    10.4.1 Introduction 482
    10.4.2 Machine tool design 484
    10.4.3 Tool design and alignment 491
    10.4.4 Chip formation and process mechanics 496
10.5 Abrasive processes – fixed and loose 505
    10.5.1 Fixed abrasive processes 505

10.5.1.1 Material removal mechanisms 505
10.5.1.2 Grinding forces, power and specific energy 512
10.5.1.3 Grinding stiffness, contact stiffness and process time constant 517
10.5.1.4 Nanogrinding 520
10.5.2 Loose abrasive processes 521
10.5.2.1 Polishing and lapping 522
10.5.2.2 Chemical mechanical planarization (CMP) 532
10.5.2.3 Process modeling in CMP 540

10.6 Non-traditional processes 551

XI. Precision manufacturing applications and challenges 555

11.1 Introduction 555
11.2 Basic semiconductor device manufacturing 559
11.2.1 Introduction 559
11.2.2 So, what are they anyway and how are they made? 561
11.2.2.1 Microfabrication: background and overview 561
11.2.2.2 Lithography 564
11.3 Applications of semiconductor manufacturing – MEMS 570
11.4 Nanotechnology 572
11.4.1 Background and definitions 572
11.4.2 Nanostructured materials 576
11.4.3 Nanofabrication techniques 578
11.4.3.1 E-beam and nano-imprint Fabrication 582
11.4.3.2 Epitaxy and strain engineering 585
11.4.3.2.1 Quantum structure nanofabrication using epitaxy on patterned substrates 585
11.4.3.2.2 Quantum structure nanofabrication using strain-induced self-assembly 587

11.4.3.3 Scanned probe techniques 589
11.4.4 Self-assembly 595
11.5 MEMS and nanotechnology applications 600
11.5.1 Nanotechnology applications 601
11.6 Micro-machining and small scale defects 604
11.6.1 Introduction 604
11.6.2 Surface and edge finish 607
11.6.3 Modeling 611
11.6.3.1 Finite element modeling 613
11.6.3.2 Molecular dynamics 615
11.6.3.3 Multiscale modeling 619
11.6.3.4 Mechanistic modeling 620
11.6.4 Workpiece and design issues 622
11.6.4.1 Micromolding 622
11.6.4.2 Creation of micropattern and microstructure 625
11.6.4.3 Creation of 3-dimensional shapes 630
11.6.4.4 Ultrasonic vibration assisted micromachining 631
11.6.5 Micro-tools 633
11.6.6 Cutting fluid 638
11.6.7 Metrology in micromachining 640
11.6.8 Conclusion and outlook 644
11.7 Burrs – preventing and minimizing burr formation in precision components 646
11.7.1 Introduction and background 647
11.7.2 Process-based solutions 651
11.7.2.1 Milling 652
11.7.2.2 Drilling 654
11.7.3 Examples of application of burr minimization strategies 657
11.7.3.1 Tool path planning in milling 657
11.7.3.2 Burr control chart 660
11.7.3.3 Integrated process planning and burr minimization 661
11.7.4 Summary and conclusions 662

XII. Future of precision manufacturing 665

12.1 Introduction 665
12.2 The manufacturing pipeline 666
12.3 Sustainable design/environmentally conscious design and manufacturing 669
    12.3.1 Technologies for sustainable manufacturing 670
    12.3.2 Green manufacturing pipeline 671
    12.3.3 Sustainable manufacturing or “does green = sustainable?” 676
    12.3.4 Manufacturing technology wedges 678
    12.3.5 Examples of wedge technology application areas for manufacturing 680
        12.3.5.1 Consumable use in machining 681
        12.3.5.2 Energy use in nanoscale manufacturing 685
12.4 Environmentally conscious design of precision machines 693
    12.4.1 Sustainability budget 694
    12.4.2 Constructing the sustainability budget 696

12.5 Summary comments/conclusion 701

References 705

Index 765