Contents

List of Contributors  XVII

1  Fundamentals  1
1.1  Roles of Sensors in Manufacturing and Application Range  1
   I. Inasaki, H. K. Tonshojf
1.1.1  Manufacturing  1
1.1.2  Unit Processes in Manufacturing  2
1.1.3  Sensors  3
1.1.4  Needs and Roles of Monitoring Systems  4
1.1.5  Trends  5
1.1.6  References  6
1.2  Principles of Sensors for Manufacturing  6
   D. Dornfeld
1.2.1  Introduction  6
1.2.2  Basic Sensor Classification  10
1.2.3  Basic Sensor Types  13
1.2.3.1  Mechanical Sensors  13
1.2.3.2  Thermal Sensors  17
1.2.3.3  Electrical Sensors  17
1.2.3.4  Magnetic Sensors  18
1.2.3.5  Radiant Sensors  18
1.2.3.6  Chemical Sensors  18
1.2.4  New Trends - Signal Processing and Decision Making  19
1.2.4.1  Background  29
1.2.4.2  Sensor Fusion  21
1.2.5  Summary  23
1.2.6  References  23
1.3  Sensors in Mechanical Manufacturing - Requirements, Demands, Boundary Conditions, Signal Processing, Communication  24
   T. Moriwaki
1.3.1  Introduction  24
1.3.2  Role of Sensors and Objectives of Sensing  24
1.3.3  Requirements for Sensors and Sensing Systems  27
3.3.3.2 Power Sensors 228
3.3.3.3 Temperature Sensors 229
3.3.3.4 Acoustic Emission Sensors 232
3.3.4 Sensors for Tools 134
3.3.5 Sensors for Workpieces 236
3.3.5.1 Eddy-current Sensors 236
3.3.5.2 Micro-magnetic Sensors 237
3.3.6 References 141

4 Sensors for Process Monitoring 243
4.1 Casting and Powder Metallurgy 143
4.1.1 Casting 243

H. D. Haferkamp, M. Niemeyer, J. Weber
4.1.1.1 Introduction 143
4.1.1.2 Sensors with Melt Contact 245
4.1.1.3 Sensors without Melt Contact 249
4.1.1.4 Summary 257
4.1.1.5 References 257
4.1.2 Powder Metallurgy 259

R. Werthelm
4.1.2.1 Introduction 259
4.1.2.2 Mixing and Blending of Metal Powders 259
4.1.2.3 Compacting of Metal Powders 262
4.1.2.4 The Sintering Process 266
4.1.2.5 References 272
4.2 Metal Forming 272

E. Doege, F. Meiners, T. Mende, W. Stmche, J. W. Yun
4.2.1 Sensors for the Punching Process 272
4.2.1.1 Sensors and Process Signals 273
4.2.1.2 Sensor Locations 274
4.2.1.3 Sensor Applications 276
4.2.2 Sensors for the Sheet Metal Forming Process 282
4.2.2.1 Deep Drawing Process and Signals 282
4.2.2.2 Material Properties 282
4.2.2.3 Lubrication 284
4.2.2.4 In-process Control for the Deep Drawing Process 286
4.2.3 Sensors for the Forging Process 292
4.2.3.1 Sensors Used in Forging Processes 292
4.2.3.2 Sensor Application and Boundaries 295
4.2.3.3 Typical Signals for Forces and Path 298
4.2.3.4 Process Monitoring 200
4.2.4 References 202
4.3 Cutting Processes 203

I. Inasaki, B. Karpuschewski, H. K. Tonshojf
4.3.1 Introduction 203
4.3.2 Problems in Cutting and Need for Monitoring 203
4.3.3 Sensors for Process Quantities 204
4.3.3.1 Force Sensors 204
4.3.3.2 Torque Sensors 209
4.3.3.3 Power Sensors 222
4.3.3.4 Temperature Sensors 222
4.3.3.5 Vibration Sensors 214
4.3.3.6 Acoustic Emission Sensors 225
4.3.4 Tool Sensors 220
4.3.5 Workpiece Sensors 225
4.3.6 Chip Control Sensors 228
4.3.7 Adaptive Control Systems 232
4.3.8 Intelligent Systems for Cutting Processes 233
4.3.9 References 234
4.4 Abrasive Processes 236
   I. Inasaki, B. Karpuschewski
4.4.1 Introduction 236
4.4.2 Problems in Abrasive Processes and Needs for Monitoring 236
4.4.3 Sensors for Process Quantities 237
4.4.3.1 Force Sensors 238
4.4.3.2 Power Measurement 239
4.4.3.3 Acceleration Sensors 239
4.4.3.4 Acoustic Emission Systems 239
4.4.3.5 Temperature Sensors 242
4.4.4 Sensors for the Grinding Wheel 244
4.4.4.1 Sensors for Macro-geometric Quantities 246
4.4.4.2 Sensors for Micro-geometric Quantities 247
4.4.5 Workpiece Sensors 249
4.4.5.1 Contact-based Workpiece Sensors for Macro-geometry 249
4.4.5.2 Contact-based Workpiece Sensors for Micro-geometry 252
4.4.5.3 Contact-based Workpiece Sensors for Surface Integrity 252
4.4.5.4 Non-contact-based Workpiece Sensors 252
4.4.6 Sensors for Peripheral Systems 256
4.4.6.1 Sensors for Monitoring of the Conditioning Process 256
4.4.6.2 Sensors for Coolant Supply Monitoring 259
4.4.7 Sensors for Loose Abrasive Processes 262
4.4.7.1 Lapping Processes 262
4.4.7.2 Sensors for Non-conventional Loose Abrasive Processes 264
4.4.8 Adaptive Control Systems 265
4.4.9 Intelligent Systems for Abrasive Processes 268
4.4.10 References 272
4.5 Laser Processing 272
   V. Krai, O. Hitters
4.5.1 Introduction 272
4.5.2 Parameter Monitoring Sensors 273
4.5.2.1 Sensors for Identifying Workpiece Geometry  273
4.5.2.2 Sensors for Identifying Workpiece Quality  273
4.5.2.3 Sensors for Beam Characterization  274
4.5.2.4 Focal Position and Gas Pressure  274
4.5.3 Quality Monitoring Sensors  275
4.5.3.1 Optical Sensors  275
4.5.3.2 Acoustic Sensors  275
4.5.3.3 Visual-based Sensing  275
4.5.4 Conclusion  276
4.5.5 References  277
4.6 Electrical Discharge Machining  277-
   T. Masuzawa
4.6.1 Introduction  277
4.6.2 Principle of EDM  278
4.6.3 Process Control  279
4.6.4 Sensing Technology  279
4.6.4.1 Gap Voltage  280
4.6.4.2 Current Through Gap  282
4.6.4.3 Electromagnetic Radiation  283
4.6.4.4 Acoustic Radiation  283
4.6.5 Evaluation of Machinery Accuracy  283
4.6.5.1 VS Method  284
4.6.5.2 Application of Micro-EDM  285
4.7 Welding  286
   H. D. Haferkamp, F. v. Alvensleben, M. Niemeyer, W. Specker, M. Zelt
4.7.1 Introduction  286
4.7.2 Geometry-oriented Sensors  287
4.7.2.1 Contact Geometry-oriented Sensors  287
4.7.2.2 Non-contact Geometry-oriented Sensors  291
4.7.3 Welding Process-oriented Sensors  295
4.7.3.1 Primary Process Phenomena-oriented Sensors  295
4.7.3.2 Secondary Process Phenomena-oriented Sensors  300
A.1 A Summary  305
4.7.5 References  305
4.8 Coating Processes  307
   K.-D. Bouzakis, N. Vidakis, G. Erkens
4.8.1 Coating Process Monitoring  307
4.8.1.1 Introduction  307
4.8.1.2 Vacuum Coating Process Classification  308
4.8.1.3 Vacuum Coating Process Parameter Monitoring Requirements  309
4.8.2 Sensors in Vapor Deposition Processes  322
4.8.2.1 Vapor Process Parameter Map  311
4.8.2.2 Vacuum Control  311
4.8.2.3 Temperature Control  318
4.8.2.4 Gas Analyzers for Coating Process Control  321
4.8.2.5 Thin-film Thickness (TFT) Controllers for Deposition Rate Monitoring and Control 322
4.8.2.6 Gas Dosing Systems and Valves 324
4.8.2.7 Other Parameters Usually Monitored During the PVD Process 325
4.8.3 References 325
4.9 Heat Treatment 326
  P. Mayr, H. Klumper-Westkamp
  4.9.1 Introduction 326
  4.9.2 Temperature Monitoring 326
  4.9.3 Control of Atmospheres 329
  4.9.4 Carburizing 329
  4.9.5 Nitriding 332
  4.9.6 Oxidizing 332
  4.9.7 Control of Structural Changes 334
  4.9.8 Quenching Monitoring 337
  4.9.8.1 Fluid Quench Sensor 338
  4.9.8.2 Hollow Wire Sensor 338
  4.9.8.3 Flux Sensor 339
  4.9.9 Control of Induction Heating 339
  4.9.10 Sensors for Plasma Processes 342
  4.9.11 Conclusions 341
  4.9.12 References 342

5 Developments in Manufacturing and Their Influence on Sensors 343
  5.1 Ultra-precision Machining: Nanometric Displacement Sensors 343 *
    E. Brinksmeier
    5.1.1 Optical Scales 343
    5.1.2 Laser Interferometers 348
    5.1.3 Photoelectric Transducers 352
    5.1.4 Inductive Sensors 352
    5.1.5 Autocollimators 352
    5.1.6 References 353
    5.2 High-speed Machining 354
      H.K. Tonshojf
    5.3 Micro-machining 357
      M. Week
    5.4 Environmental Awareness 363
      F. Klocke
      5.4.1 Measurement of Emissions in the Work Environment 364
      5.4.1.1 Requirements Relating to Emission Measuring Techniques in Dry
        Machining 364
      5.4.1.2 Sensor Principles 364
      5.4.1.3 Description of Selected Measuring Techniques 365
      5.4.1.4 Example of Application 366
      5.4.2 Dry Machining and Minimum Lubrication 367
5.4.2.1 Measuring Temperatures in Dry Machining Operations 367
5.4.2.2 Measuring Droplets in Minimal Lubrication Mode 368
5.4.3 Turning of Hardened Materials 369
5.4.3.1 Criteria for Process and Part Quality 369
5.4.3.2 Sensing and Monitoring Approaches 372
5.4.4 Using Acoustic Emission to Detect Grinding Burn 372
5.4.4.1 Objective 373
5.4.4.2 Sensor System 374
5.4.4.3 Signal Evaluation 375
5.4.5 References 375

List of Symbols and Abbreviations 377

Index 383