

Contents

1	Measurement and Machine Tools—An Introduction	1
1.1	Why the Need for Accurate and Precise Machine Tools—a Brief History	1
1.2	The Early Historical Development of a Linear Measurements	4
1.2.1	The Historical Development of the Metre and the International Bureau of Weights and Measures (BIPM)	9
1.2.2	Optical and Laser Length Measurement	12
1.3	International Standards Laboratories—Why They Are Essential	14
1.3.1	What Is Traceability and Why Is It Necessary?	15
1.3.2	Auditing Metrology: Artefacts, Instrumentation and Equipment	19
1.3.3	National Metrological Research and Calibration Laboratories	22
1.4	Machine Tool's Machining Capabilities	32
1.5	Metrology Equipment Utilised for Basic Machine Tool Calibration Checks	37
1.5.1	Gauge Blocks	37
1.5.2	Length Bars	41
1.5.3	Combination Angle Gauges	44
1.5.4	Precision Polygons	46
1.5.5	Dial Gauges and Dial Test Indicators	48
1.5.6	Straightedges and Cylindrical Precision Mandrels	53
1.5.7	Precision- and Cylindrical Squares	59
1.6	A Concise History of Machine Tool Calibration	62
1.7	Notable Chronology in Machine Tool Testing	67
1.8	Achievable Accuracy and Precision of Machine Tools	69
1.9	Accuracy and Precision—Produced by a Machine Tool	74
1.10	Designation of Machine Tool Axes and Kinematics	84
1.11	Configurations of Machining and Turning Centres	90

1.11.1	Orthogonal Machine Tools	90
1.11.2	Modular, or Reconfigurable Machine Tools	90
1.11.3	Modular Machine Tool Construction	93
1.11.4	Turning and Machining Centre Configurations	95
1.11.5	CNC Controller Developments	101
1.11.6	Non-orthogonal/Parallel Kinematic Machines (PKM).	103
1.12	Major Elements in a Machine Tool's Construction	107
1.12.1	Headstocks for Turning Centres and Spindles for Machining Centres	108
1.12.2	CNC Conventional Drive Systems and Recirculating Ball screws	114
1.12.3	Machine Tool—Bearing Categories	126
1.12.4	Constructional Elements for Machine Tools	143
1.12.5	Linear Motor Drive Systems	154
1.12.6	Linear and Rotary Axis Positioning/Monitoring Systems.	159
1.13	Finite Element Analysis (FEA) of Machine Tools	177
1.13.1	FEA of CNC Machine Tools	179
1.13.2	Industrial Machine Tool Case Study in FEA—for a Machining Centre.	180
1.14	Basic Construction of Coordinate Measuring Machines (CMMs).	183
1.14.1	Introduction to the CMM	183
1.14.2	CMM Construction	187
1.14.3	CMM—Mechanical Probe	188
1.14.4	Recent CMM Probing Systems	190
1.14.5	Micro-Metrology Probes	194
	References	195
2	Laser Instrumentation and Calibration	201
2.1	Introduction to Lasers.	201
2.1.1	Why Is Calibration so Important?	202
2.1.2	Calibration of Laser Interferometers	203
2.1.3	Laser Calibration—Potential Error and Uncertainty Sources	205
2.1.4	Introduction to Laser Machine Calibration	211
2.2	Methods of Machine Acceptance Tests—The Basis for Verification	214
2.2.1	ISO 230 Machine Tool Standards—Previous and Current Calibration Procedures	214
2.2.2	ISO 230—Laser Calibration Procedures on CNC Machine Tools	219
2.2.3	Laser Diagonal Displacement Test.	222
2.2.4	Laser Step Diagonal Test	230
2.2.5	Potential Errors—In Three Axes Machine Tools	236
2.3	ISO 10360 for Coordinate Measuring Machine (CMM) Calibration and Verification	245

2.3.1	Coordinate Measuring Machine (CMM)—Fundamentals . . .	246
2.3.2	CMM—Environmental Conditions	253
2.3.3	CMM Performance Standards	253
2.4	Calibration of a Rotary Table—With a Rotary Indexer	255
2.4.1	AxisSet™ Checkup—Utilised for Machine Tool Alignments	259
2.5	Machine Tool Linear Axes—Factors Affecting Their Accuracy and Precision	261
2.6	Laser Tracker—Instrumentation, Testing and Applications	264
2.6.1	Laser Tracker—Calibration Procedures	267
2.6.2	Laser Tracker—Frequently Asked Questions	268
2.6.3	Laser Tracker—Machine-Based Research Applications	270
	References	274
3	Optical Instrumentation for Machine Calibration	279
3.1	Basic Principles of Light	279
3.1.1	Optical Alignment—Basic Principles	284
3.2	Autocollimation Principles	287
3.2.1	Basic Design of an Autocollimator	287
3.2.2	Autocollimator—its Optical Operational Principle	290
3.2.3	Digital Autocollimators	291
3.2.4	Precision Polygons for Angular Measurements	296
3.2.5	Angular Calibration of a Precision Polygon	297
3.2.6	Calibration of a Rotary Table	299
3.3	The Micro-optic Dual-Axis Autocollimator, or Angledekkor	300
3.3.1	Optical Squares and Prisms	302
3.4	Alignment Telescope—Principles of Alignment	305
3.4.1	Targets for Autocollimators	316
3.4.2	Auto-reflection and Autocollimation	317
3.4.3	Calculating Mirror Gradients	319
3.4.4	Effects of the Earth's Curvature and Atmospheric Refraction	320
3.5	Precision Spirit Level	323
3.6	Optical Instrumentation—Clinometers	328
3.7	Talyvel—Precision Level	333
3.7.1	Software Programs—for Precision Electronic Levels	337
	References	342
4	Telescoping Ballbars and Other Diagnostic Instrumentation	345
4.1	Telescoping Ballbars	345
4.1.1	Machine Tool Health Checks—The Reason Why They Are Necessary	345
4.1.2	Telescoping Ballbars—Historical Development and Operation	346
4.1.3	Telescoping Ballbar—In More Detail	354
4.1.4	Ballbar Testing—Why the Need?	354

4.1.5	Wireless Telescoping Ballbar	356
4.1.6	Telescoping Ballbar—A Closer Examination of Machine Tool Inaccuracies	359
4.1.7	Ballbars—Other Instrumental Variations	360
4.2	Grid Encoders and Linear Comparator Systems	366
4.3	Rotary Analyzer System and Calibration Rings	372
4.4	Calibration Spheres and Rings—for CMMs	375
	References	378
5	Artefacts for Machine Verification	381
5.1	Introduction to Artefact Verification—For Interim CMM Checks . . .	381
5.1.1	An Introduction to CMM Error Sources	382
5.1.2	ISO 10360 and CMM Performance	382
5.1.3	Material Standard of Size and CMM Accuracy	385
5.1.4	CMM—Length Measurement and Maximum Permissible Errors	392
5.2	Purpose-Made Artefacts—Testpieces	393
5.3	General Artefacts for CMM Verification	394
5.3.1	Step Gauge—Its Calibration	394
5.3.2	Step Gauge—For Verification of the Accuracy of CMMs . . .	395
5.3.3	Machine Checking Gauge (MCG)	399
5.4	Ball- and Hole-Plates	406
5.4.1	The 3-D Ball-Plates	410
5.4.2	Ball- and Cube-Tetrahedrons	413
5.5	Large Reference Artefact—For Large-Scale CMM Verification . . .	416
5.5.1	Large Reference Artefact (LRA)—Design and Construction	418
5.5.2	Large Reference Artefact—Reference Surfaces	419
5.5.3	Large Reference Artefact—Artefact Positioning, Alignment and Testing	422
5.5.4	Large Reference Artefact—Summary and Concluding Remarks	423
5.6	Machinable-Artefacts for Machine Tool Verification	424
5.6.1	Introduction to Machinable Testpiece Standards	424
5.6.2	Artefact Stereometry—For Dynamic Machine Tool and Comparative Assessment	426
5.6.3	Stereometric Artefact—Conceptual Design	427
5.6.4	Stereometric Artefact—Machining Trials	429
5.6.5	Stereometric Artefact—Machined and Metrological Results	435
5.7	Small Coordinate Measuring Machine (SCMM)	438
5.7.1	Small Coordinate Measuring Machine—Design Requirements	438
5.7.2	Small Coordinate Measuring Machine—Interferometers, Autocollimators and Probe Design	441
5.8	A Novel 3-D-Nano Touch Probe—For an Ultra-Precision CMM . . .	443

5.8.1	Probing Force and Surface Damage	445
5.8.2	The 3-D-Nano Touch Probe—Constructional Details	445
5.9	Robotic Arms	447
5.9.1	Industrial Robotics—Their Historical Development	448
5.9.2	Defining Robotic Parameters	449
5.9.3	Robotic Calibration	451
5.9.4	Robotic Calibration Devices and Techniques	453
5.10	Parallel Kinematic Mechanism (PKM)—Equator™ Gauge	457
5.10.1	Theory of Operation—Of the PKM	459
5.10.2	Calibrating This PKM	460
5.11	Articulated Arm CMM (AACMM)	461
5.11.1	Articulated Arm CMMs—In More Detail	465
5.11.2	Verification of Articulated Arm CMM (AACMM)	467
	References	468
6	Machine Tool Performance: Spindle Analysis; Corrosion and Condition Monitoring; Thermography	473
6.1	Machine Tool Spindle Analysis	473
6.1.1	Design Trends in Machine Tool Spindles	475
6.1.2	Machine Tool Spindle Failure Modes	478
6.1.3	Complete Machine Tool Retrofits and Rebuilds	485
6.2	Monitoring and Diagnostics of Machine Tool Spindles	495
6.2.1	Spindle Monitoring Instrumentation—For Machine Tools	496
6.2.2	Thermal Distortion—At the Spindle	496
6.2.3	Spindle Error Motions	497
6.3	Spindle Error Analyser (SEA) Instrumentation	498
6.3.1	Spindle Error Analyser—The Master Target and Its Fixtures—Spindle Hardware	503
6.3.2	Spindle Error Analyser—Spindle Software	504
6.3.3	SEA—Thermal Drift—Resulting from Expansion of Materials	504
6.3.4	SEA—Thermal Tests	505
6.3.5	SEA—How Spindle Measurement Data is Displayed	506
6.3.6	SEA—Spindle Error Plots: For Analysis and Rectification of Bearings	506
6.4	Corrosion—Basic Concepts	507
6.4.1	Understanding Metallic Corrosion—In Brief	510
6.4.2	Machine Tool Spalling—of Bearings and Gears	514
6.4.3	Bearing Failure Modes—With Hard Particle Lubricant Contamination	514
6.4.4	Bearing Contamination	518
6.5	Condition Monitoring—Of Machine Tools	519
6.5.1	Condition Monitoring—Historical Perspective	521
6.5.2	Types of Condition Monitoring Systems	523
6.5.3	Condition Monitoring Systems—Establishing a Programme	524

6.6	Thermographical Inspection.	527
6.6.1	Electromagnetic Spectrum—A Brief and Introductory History	527
6.6.2	Thermography—Further Information	532
6.6.3	Thermal Imaging Cameras	535
6.6.4	Emissivity—Thermal Radiation.	537
6.6.5	Advantages and Limitations of Thermography	538
6.6.6	Effects of Temperature Variation in Machine Tools.	539
6.6.7	Controlling Component Part Temperatures	543
6.6.8	Minimising Heat Sources.	543
6.6.9	Temperature Control Strategies	544
	References.	546
7	Uncertainty of Measurement and Statistical Process Control	551
7.1	Conformance, Traceability and Measurement Uncertainty	551
7.2	Task-Specific Measurement Uncertainty	555
7.2.1	Traceability Reporting	555
7.2.2	Conformance Rules—for Metrological Equipment	558
7.3	Measurement Uncertainty—Typically Relating to Machine Tools and CMMs.	561
7.3.1	Statements of Compliance—The Effect of Uncertainty.	566
7.3.2	Uncertainty Issues	566
7.3.3	Statistical Measures—In Uncertainty Calculations	567
7.3.4	Origins of Uncertainties	574
7.3.5	Calculation of Measurement Uncertainty.	575
7.3.6	Analysis of Uncertainty: Uncertainty Budgets.	580
7.3.7	Reducing Measurement Uncertainty	584
7.4	Statistical Process Control (SPC)—In Production Output on Machine Tools	585
7.4.1	What is Statistical Process Control?.	586
7.4.2	Control Chart Functions	587
7.4.3	Control Chart—Background Information	589
7.4.4	Control Chart Limits	591
7.4.5	Reading Control Charts	594
7.4.6	Computerised SPC Charts	596
7.5	Machine and Process Capability Studies	598
7.5.1	Machine and Process Capability Studies—Typical Procedure	598
7.5.2	Machine Capability Study—In Detail	599
7.5.3	Machine Tool Capability Study—Practical Example.	601
7.5.4	Final Concluding Remarks.	605
	References.	605
	Appendices.	609
	Index.	671

<http://www.springer.com/978-3-319-25107-3>

Machine Tool Metrology

An Industrial Handbook

Smith, G.T.

2016, XIX, 685 p. 258 illus., 191 illus. in color.,

Hardcover

ISBN: 978-3-319-25107-3