

Contents

Contents	I
Symbols and Abbreviations	V
1 Introduction	1
2 Fundamentals and State of the Art	3
2.1 Technology of Circle Segment End Mills	3
2.1.1 Basic Concept	3
2.1.2 Tool Types and Characteristics	4
2.1.3 Related Research Activities	6
2.1.4 Differentiation of Surface Types	10
2.1.5 Interim Conclusion	11
2.2 Process Modeling in 5-Axis Milling	13
2.2.1 Process Classification	13
2.2.2 Inclined Milling Kinematics	13
2.2.3 Cutting Tool Geometry	15
2.2.4 Force Modeling	17
2.2.5 Cutter-Workpiece Engagement Modeling	23
2.3 Adaptive Milling	27
2.3.1 Offline vs. Online Process Control	27
2.3.2 Offline Force Control in Milling	28
2.4 Summary	31
3 Research Aim and Methodology	33
4 Influence of Surface Topography and Tool Orientation on Machinability	35
4.1 Process Forces	35
4.1.1 Experimental Setup	35
4.1.2 Influence of Tool Orientation	37
4.1.3 Influence of Surface Topography	39
4.2 Surface Quality	42
4.2.1 Experimental Setup	42
4.2.2 Influence of Tool Orientation	43
4.2.3 Influence of Surface Topography	47
4.3 Tool Wear	50
4.3.1 Experimental Setup	50
4.3.2 Influence of Tool Orientation	51
4.4 Summary	51
5 Engagement and Force Modeling	55
5.1 Requirements and Assumptions	55
5.2 Macroscopic Engagement Modeling	56
5.3 Microscopic Engagement Modeling	58
5.3.1 Fundamental Chip Thickness Calculation	58
5.3.2 Feed Vector Decomposition	59
5.3.3 Curvature Angle	62

5.3.4	Advanced Chip Thickness Calculation	63
5.3.5	Correction Angle	65
5.3.6	Uncut Chip Geometry	65
5.4	Model Adaption to Circle Segment End Mills	67
5.4.1	Analytical Modeling of Tool Macro Geometry	67
5.4.2	Integration with the Engagement Model	68
5.5	Force Modeling	70
5.6	Software Architecture	71
5.7	Summary	72
6	Model Validation and Sensitivity Analysis	75
6.1	Model Variants	75
6.2	Identification of Specific Force Coefficients	76
6.2.1	Calibration Variant 1 - Constant Helix Angle	77
6.2.2	Calibration Variant 2 - Variable Helix Angle	79
6.2.3	Calibration Variant 3 - Singular Mechanistic Calibration	81
6.3	Engagement and Force Simulation	82
6.3.1	Model Variant 1 - Constant Helix Angle and Variable Calibration	82
6.3.2	Model Variant 2 - Variable Helix Angle and Variable Calibration	91
6.3.3	Model Variant 3 - Constant Helix Angle and Constant Average Calibration	95
6.3.4	Further Model Variants	99
6.4	Comparison of Prediction Accuracy	102
6.5	Summary	103
7	Adaptive Milling with Circle Segment End Mills	107
7.1	Force-Based Adaptive Milling Strategy	107
7.1.1	Feed Rate Scheduling Strategy	107
7.1.2	Tool Orientation Scheduling Strategy	110
7.2	Software Architecture	111
7.2.1	Implementation of Feed Rate Scheduling	112
7.2.2	Implementation of Tool Orientation Scheduling	112
7.3	Experimental Validation	113
7.3.1	Experimental Setup	113
7.3.2	Non-Adaptive Milling Study	115
7.3.3	Feed Rate Scheduling Trials and Validation	116
7.3.4	Tool Orientation Scheduling Trials and Validation	120
7.4	Retrospective Discussion of Feed Vector Decomposition	122
7.5	Step-Over Distance Scheduling	126
7.6	General Productivity Assessment	129
7.7	Summary	131
8	Summary and Outlook	135
	Bibliography	139
A	Appendix	159
A.1	Differentiation of Surface Types	159
A.1.1	Planar Surfaces	159
A.1.2	Ruled Surfaces	159
A.1.3	Free-Form Surfaces	160

A.2	Oblique Tilt and Lead Angle β_{fN}' / β_f'	161
A.2.1	Derivation of the Oblique Tilt and Lead Angle β_{fN}' / β_f'	163
A.3	Variation Angle $\varphi_{v,min} / \varphi_{v,max}$	164
A.3.1	Derivation of the Variation Angle for $\varphi_{v,min} < 90^\circ$	164
A.3.2	Derivation of the Variation Angle for $\varphi_{v,min} > 90^\circ$	165
A.3.3	Derivation of the variation angle for $\varphi_{v,max} < 90^\circ$	165
A.3.4	Derivation of the Variation Angle for $\varphi_{v,max} > 90^\circ$	165
A.4	Geometry Models for Ball End Mill and Circle Segment End Mills	166
A.4.1	Ball End Mill	166
A.4.2	Circle Segment End Mill - Drop Shape	166
A.4.3	Circle Segment End Mill - Drop Shape with Conical Shaft	169
A.4.4	Circle Segment End Mill - Conical Shape	171
A.5	Mathematical Assessment of Correlation Diagrams and Model Performance	175
A.6	Convergence Study - Total Force vs. Discretization	175
A.7	Non-Adaptive Milling Study - Total Force	177
A.8	Adaptive Feed Rate Scheduling Trials and Validation - Simulation Results for Smoothed and Minimum Envelope Feed Rate	178
A.9	Adaptive Step-Over Distance	180
A.9.1	Calculation of Adaptive Step-Over Distance	180
A.9.2	Calculation of Adaptive Step-Over Tool Path	182
A.10	Experimental Data	185
A.11	Calibration Data	187
A.12	Simulation Data	191
A.13	Engagement Charts: Circle Segment End Mill	207
A.14	Engagement Charts: Ball End Mill	233